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PRELIMINARY GUIDELINES FOR SAFE AND EFFECTIVE USE
OF HOT, HIGH-PRESSURE WASHERS
FOR MAINTENANCE CLEANING OF ARMY VEHICLES
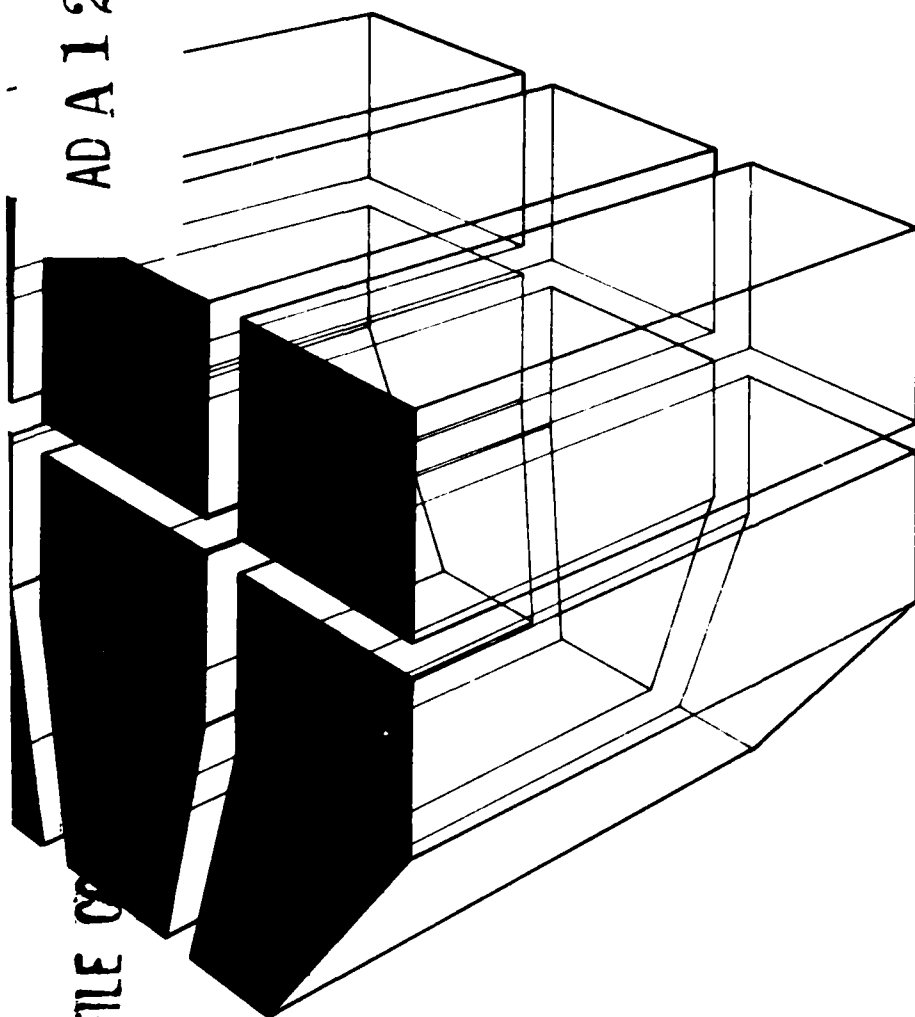
by
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J. E. Matherly
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R. J. Scholze

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While hot, high-pressure washers clean effectively, they can also damage parts on Army vehicles. The objective of this study was to develop preliminary guidance for selecting vehicle maintenance cleaning equipment and its operational settings. Development of these guidelines was to take into account: (1) maximum cleaning effectiveness; (2) minimum risk of damage to vehicle components; and (3) minimum safety hazard to personnel.

To achieve this objective, the U.S. Army Construction Engineering Research Laboratory (CERL) conducted a literature search and contacted cleaning equipment industries

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·for current information. A theoretical analysis of operating variables was then conducted to identify those most likely to influence damage to components of Army vehicles. Next, vehicle parts were physically tested. These tests were divided into a lab phase, which addressed the damage issue, and a field phase, which concerned cleaning effectiveness and safety. Finally, the data from the background studies and the two phases of physical testing were combined to make final recommendations about selecting and operating maintenance cleaning equipment.

From the results of the lab phase of this study, it can be concluded that there are no absolutely safe operational settings below which damage cannot occur and above which it will always occur. From the results of the field phase of this study, it can be concluded that the washer's pressure and temperature–above minimums of 500 psi (3445 kPa) and 110°F (43°C)–have little effect on the time required to clean any particular vehicle. ·

To achieve effective maintenance cleaning and to lessen the risk of damage to Army vehicles and injury to Army personnel, it is recommended that hot, high-pressure washers used for maintenance cleaning be adjusted to a pressure of 800 psi (3510 kPa) and a temperature of 130°F (54°C) (both measured at machine output), and be equipped with a 25-degree nozzle sized to provide a flow rate of about 3.5 gpm (13.2 L/min). It must be emphasized that even at these recommended settings, some risk of damage still exists; therefore, operators must be trained to be careful when cleaning near sensitive items such as oil seals and electrical connectors. Distances of 6 in. (152 mm) or more should be maintained between the nozzle and the part being cleaned, and the spray should not be concentrated on any one spot for more than 5 seconds.

FOREWORD

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PRELIMINARY GUIDELINES FOR SAFE AND EFFECTIVE USE OF HOT, HIGH-PRESSURE WASHERS FOR MAINTENANCE CLEANING OF ARMY VEHICLES

1 INTRODUCTION

Background

Maintenance cleaning is performed on virtually all Army vehicles. Engine compartments are routinely cleaned before scheduled quarterly maintenance, unscheduled repairs, and regular inspections. This work is done regularly at some 3000 maintenance shops and 2000 washracks in the continental United States,[1] and at overseas facilities. Proper cleaning of mechanical components is essential to proper maintenance, which in turn is essential to equipment readiness.

At most Army installations, maintenance cleaning at the washracks is done with cold, low-pressure water and solvents; at the maintenance shops steam cleaners and detergents are used. Neither of these methods is very effective, and both produce wastewater which is difficult to treat because of soaps, solvents, and emulsified oils. To correct this, the U.S. Army Construction Engineering Research Laboratory (CERL) has advocated using hot, high-pressure water washers. One of the main advantages of these units is that they effectively remove oily dirt without the need for soaps or solvents. The latest CERL report on this topic evaluated the washers and the wastewater characteristics at Fort Lewis, WA.[2]

The use of hot, high-pressure washers for maintenance cleaning fits into an overall concept developed at CERL for redesign of vehicle cleaning operations on Army installations. In this concept, exterior cleaning is separated from maintenance cleaning to facilitate wastewater treatment as well as to improve operational efficiency.

While hot, high-pressure washers clean effectively, they can also damage components. At very high pressures and temperatures, it is possible to penetrate seals

and cut rubber components. The U.S. Army Tank and Automotive Command (TACOM) became concerned about this when it was learned that one installation had acquired a washer operating at 6000 psi (41 340 kPa). Also contributing to TACOM's concern were the scattered reports of water damage coming in from other installations. TACOM recognized that a potentially large-scale problem could develop rather suddenly if Army installations continued to procure hot, high-pressure washers without the benefit of guidance specifications and information about safe but effective operational settings. TACOM asked CERL to develop such guidelines, substantiated by tests of cleaning equipment's effects on Army vehicles.

Objective

The overall objective of this research is to upgrade Army washrack facilities in order to minimize negative environmental impacts, conserve water resources, and reduce the costs of wastewater treatment. The objective of the phase of the research reported here was to develop preliminary guidance for selecting vehicle maintenance cleaning equipment and its operational settings. Development of these guidelines was to achieve: (1) maximum cleaning effectiveness; (2) minimum risk of damage to vehicle components; and (3) maximum safety for personnel.

Approach

1. To achieve this objective, CERL first conducted a literature search and contacted cleaning equipment industries for current information. A theoretical analysis of operating variables was then conducted to identify those which contributed most to the damage of components on Army vehicles. It was theorized that damage would correlate directly with the impact energy a high-pressure spray imparted to a component. By determining how the operating variables affected impact energy, CERL learned how they contributed to vehicle damage.

2. To provide TACOM with the substantiated guidance they requested, it was necessary to go beyond industry surveys and theoretical analysis. Thus, physical testing of actual components was done. These tests were divided into a lab phase, which addressed the damage issue, and a field phase, which addressed cleaning effectiveness and safety. The lab phase was necessary not only to control the parameters involved for a more accurate assessment of the potential for damage, but also to avoid putting Army vehicles out of service. Cleaning effectiveness was evaluated in the field to obtain realistic conditions of vehicle dirtiness and operator efficiency. Safety was evaluated qualitatively

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[1] Based on 1980 Real Property Inventory for U.S. Installations, Catalog Code 214.

[2] R. Fileccia, S. Kloster, L. Benson, M. Kamiya, J. Matherly, *Pretreatment of Waste Discharges From Improved Army Tactical Equipment Maintenance Facilities*, Technical Report N-107/ADA105081 (U.S. Army Construction Engineering Research Laboratory [CERL], 1981).

from observations of the troops during cleaning operations at Fort Knox, KY, and from CERL's experience with cleaning operations at other posts.

3. The data from the background studies and the two phases of physical testing were combined to make the final recommendations about selecting and operating hot, high-pressure washers.

Scope

Because of limitations on time and resources, all components of all Army vehicles could not be tested. Through discussions with TACOM, it was agreed to limit the study to three components on the M113 (armored personnel carrier): the final drive input shaft seals, radiator hoses, and electrical connectors. These components were chosen because of their vulnerability, sensitivity, and history of problems with water damage. Since these parts were believed to be more sensitive than any others, it was reasoned that if they could withstand the cleaning, so could the other components in the engine compartment.

As the study progressed, more components were made available for testing. There was enough time to test many of these, so the scope of the study was expanded somewhat.

Although a number of components were tested, this study dealt only with a small percentage of all parts found on Army vehicles. Therefore, it must be emphasized that the findings of this research are limited, and that the recommendations made are tentative and subject to change with further work. Despite these limitations, however, some extrapolation is justified since sensitive components were studied and similar components are used on all Army vehicles.

2 TESTING PROCEDURES

Laboratory Phase

In the lab phase of this study, potential damage to Army vehicle components was examined. Parts were mounted on a test stand and exposed to various intensities of water spray (Figure 1). CERL procured a custom-built pressure washer that could be adjusted through a wide range of pressure and temperature settings, allowing testing of Army vehicle components under a variety of conditions (Figure 2). Pressures ranged from 200 to 3000 psi (1380 to 20 670 kPa), and temperatures ranged from 45 to 200°F (7 to 93°C). Flow rates were varied from 1.5 to 8.0 gpm (5.7 to 30.3 L/min) and spray angles of 40, 25, 15, and 0 degrees were attained by changing the nozzle used. To monitor pressure and temperature, gauges were installed at the machine outlet. A turbine flowmeter was mounted in the water supply line to monitor flow rate.

Figure 1. Test stand with parts. Parts being tested are (from left): final drive, spider joint, electrical connector, radiator hose, and hydraulic hose.

Figure 2. Hot. high-pressure washer used in lab study.

The three main vehicle components examined in detail were final drive seals. radiator hose, and electrical connectors. The following parts also were tested as time allowed: tie-rod boots, a second type of radiator hose, hydraulic hose, V-belts, spider joints, and spark plug leads.

In the initial testing, only four operating parameters were studied: pressure, temperature, flow rate, and nozzle angle. It was realized that time of exposure and distance the nozzle was held from the component could also affect the amount of damage. However, since these parameters could not be controlled in the field, it was considered more realistic to leave them uncontrolled in the lab testing. The approach was to control the first four parameters, while simulating wash_ conditions in the field; it was assumed that this would produce the most applicable data. However, these tests yielded highly inconsistent results, depending on the experimenter's washing technique. It was then realized that the exposure time and the distance from nozzle to component had to be controlled in the testing procedure. Thus, further tests were conducted with all six parameters being controlled.

Final Drive Input Seals

Final drive input seals were tested on a final drive gearbox which was mounted on the test stand in a position similar to that found on an armored personnel carrier (APC) (Figure 3). Seal failure was defined as having occurred when water entered the gearbox. Although this water might not cause early failure of

the final drive, it is undesirable because it could lead to corrosion of internal parts and breakdown of the lubricant. To determine when a potentially damaging amount of water entered, two wires connected to an ohm-meter were installed in the lower part of the gearbox. An accumulation of water completed the circuit and produced a reading on the ohm-meter.

Three different seals were tested. In any given test, the seal was subjected to washings using various combinations of pressure, temperature, flow rate, and nozzle spray angle to determine the conditions under which the seal would fail. In each test, the nozzle was held for 10 seconds at distances of 0, 1, and 3 in. (0, 25, and 76 mm) from the seal.

Radiator Hose

Segments of hose were mounted on the test stand, filled with water, and capped at both ends to simulate conditions on an actual vehicle. Failure of this component could not be assessed quantitatively since tests revealed a range of damage which might or might not lead to eventual failure; however, damage was qualitatively assessed. For these tests, pressure, flow rate, and nozzle spray angle were studied. An ambient water temperature, 10-second time exposure, and distances of 0, 1, and 3 in. (0, 25, and 76 mm) were used throughout the hose testing.

Electrical Connectors

Electrical connectors were tested similarly to the final drive seals. Wiring was connected to alternate pins

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Figure 3. Final drive seal being tested in lab study.

so that when water entered, a reduction in the electrical resistance between pins would be indicated on the ohm-meter. It was not known whether a small accumulation of water would definitely cause early failure of the electrical connector, but with time it could corrode the pins, resulting in a poor electrical connection, and is therefore undesirable.

One new and two used connectors were subjected to washings in which pressure, temperature, flow rate, nozzle angle, and distance were varied. A 5-second exposure time was the only parameter held constant.

Board Tests

For final drive and electrical connector seals, failure was clearly defined as the point at which water entered the component. However, definition of vehicle component failure is often more subjective than this. For example, radiator hose went through many stages of damage, ranging from small tears and abrasions to deep surface cuts, before there was a catastrophic failure such as a puncture. Because of this, a method was developed to help analyze radiator hose damage. Many segments of hose were systematically tested and mounted on display boards; this permitted an organized study of the damage (Figures 4 through 7). V-belting also lent itself to this type of testing. Since the procedure was very efficient, CERL decided to test the two components at the same time. A jig was constructed so that the hose and belt could be repositioned quickly for each test.

Pressure, temperature, flow rate, nozzle angle, time, and distance were studied. It was realized that examining all combinations of these six parameters would require hundreds of tests. To reduce this number, CERL performed a systematic analysis. One board was produced concentrating on each of the four field-controllable parameters pressure, temperature, flow rate and nozzle angle. The procedure was to test a parameter in detail on one board, choose the best setting, and then hold it constant for the subsequent board tests. After the board tests and the field tests described below, the optimum operational settings were determined, and a summary board was generated to illustrate the effects of time and distance at these settings (Figure 8). Detailed results of the board tests appear in Chapter 3.

Field Phase

The field phase of the study, conducted at Fort Knox, KY, was concerned with the cleaning effectiveness and safety aspects of hot, high-pressure washing. Since APCs were chosen as representative vehicles to study, it was decided to perform the field investigation at three maintenance shops within the 4th Battalion of the 54th Mechanized Infantry, where the greatest number of APCs were available. Although this study concentrated on the M113 family of vehicles (including the M113, M577, M106, and M109), other vehicles were examined: jeeps, 2-1 2-ton (2-1/4-MT) trucks, 5-ton (4-1/2-MT) trucks, goats, and tracked recovery vehicles.

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Figure 3. Final drive seal being tested in lab study.

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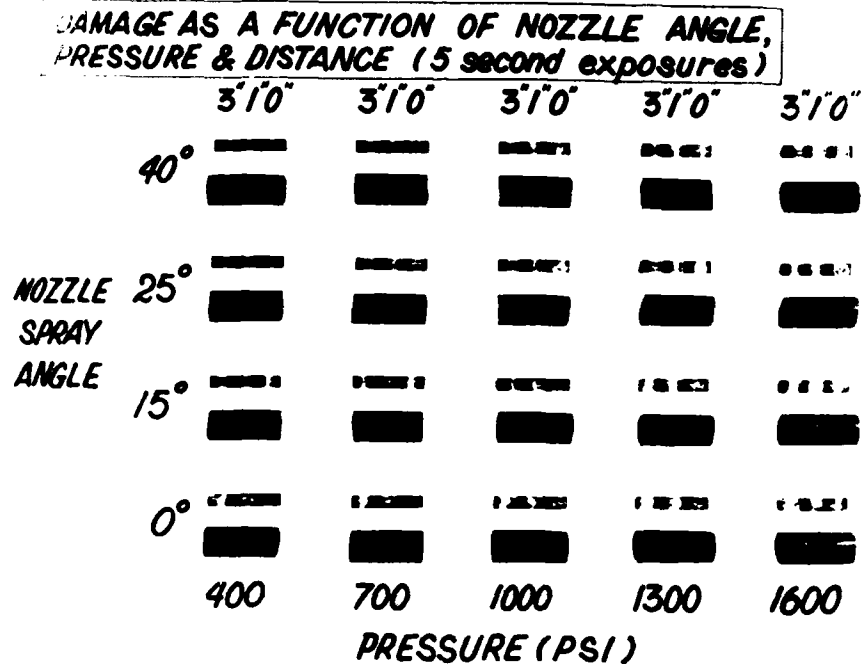**Figure 4.** Damage as a function of nozzle angle, pressure, and distance.
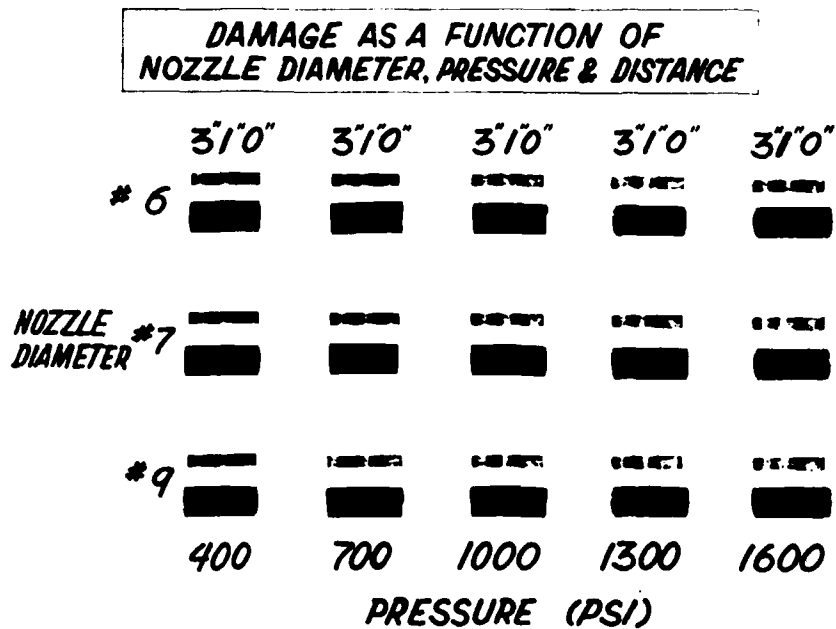

Figure 5. Damage as a function of nozzle diameter, pressure, and distance.

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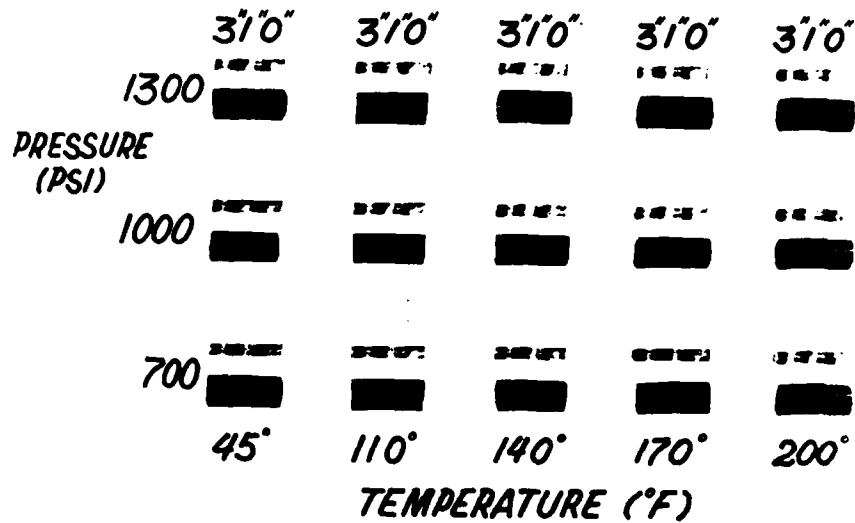## DAMAGE AS A FUNCTION OF TEMPERATURE, PRESSURE & DISTANCE

Figure 6. Damage as a function of temperature, pressure, and distance.

DAMAGE AS A FUNCTION OF DISTANCE, PRESSURE & TIME
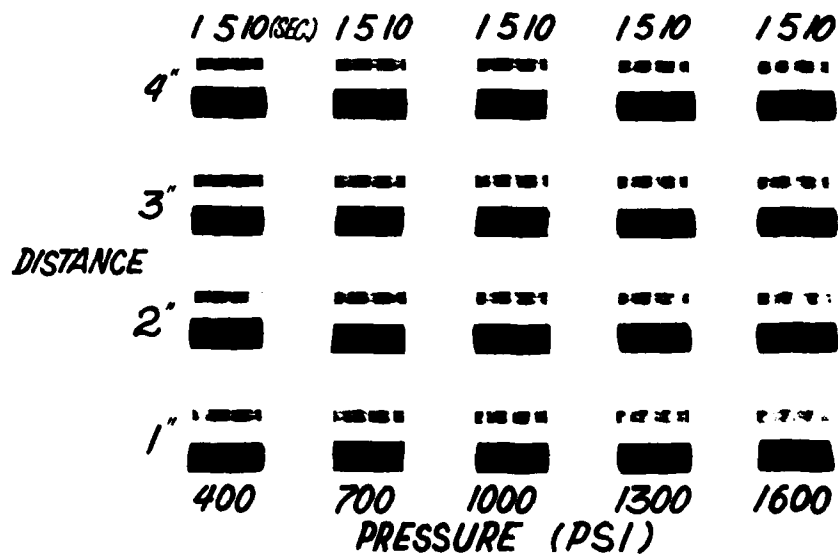
Figure 7. Damage as a function of distance, pressure, and time.

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POTENTIAL DAMAGE AS A FUNCTION OF TIME & DISTANCE AT RECOMMENDED SETTINGS

TIME (SECONDS)

10
5
1

DISTANCE (INCHES)

4   3   2   1   0
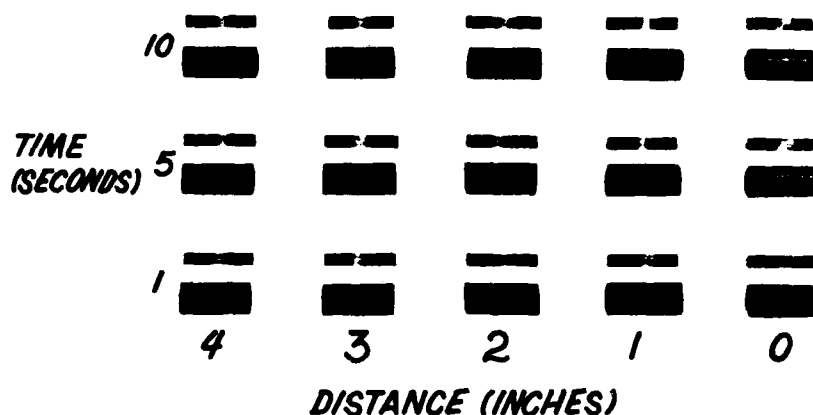
*800 PSI, 130°F, *9-25° NOZZLE

Figure 8. Potential damage as a function of time and distance at recommended settings.

At the beginning of the study, three pressure washers were delivered to Fort Knox. They were set to pressures of 500, 1000, and 1500 psi (3445, 6890, and 10 335 kPa) and a temperature of 110°F (43°C). The flow rate for all machines was about 3.5 gpm (13.2 L/min) and 25-degree nozzles were used. Water meters were installed on the washers and the machines were tested for proper operation. At this point, soldiers were trained to use the equipment.

For the field investigation, three researchers gathered data for two weeks. Cleaning effectiveness was evaluated by the amount of water consumed and the time needed to wash a vehicle. Maintenance cleaning areas were defined as engine compartments and any other vehicle areas that accumulate oil and greasy dirt. Data on maintenance cleaning were recorded separately from the cleaning data for other parts of the vehicle. Figure 9 shows a soldier cleaning the engine compartment of an APC. Figure 10 shows a jeep pack being cleaned in preparation for maintenance.

CERL researchers began a typical washing observation by recording the water meter reading, the time

washing started, and the area of the vehicle being washed. Whenever a different area of the vehicle was cleaned, another set of entries was made. Troops were allowed to wash the vehicles as they normally would, with little interference. A typical field operation is shown in Figure 11.

During each washing, qualitative observations were made concerning cleaning effectiveness and safety for the operator. At the end of the cleaning period, each vehicle was examined for damage, and the operators' reactions to the equipment were recorded. The troops' ideas for improvement of the high-pressure washers were also noted (see Chapter 3).

During the 2 weeks of field investigation, the plan at first was to study temperature's effect on cleaning by changing the temperature setting on the three machines every 1 to 2 days. For a valid comparison, several washings at each temperature would be required. Because of the limited number of vehicles being washed, however, this procedure could not be used. Instead, a small-scale temperature analysis was done. This consisted of cleaning a shop maintenance

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Figure 9. APC engine compartment being cleaned during field study.
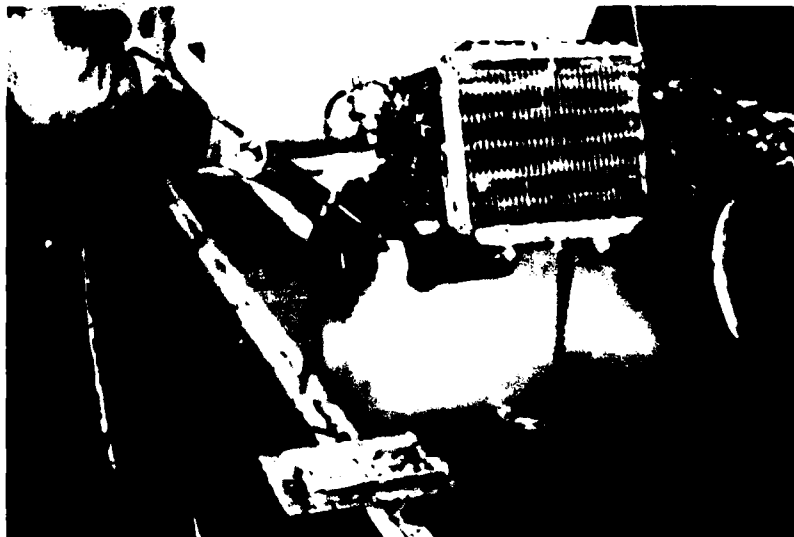
Figure 10. Jeep engine pack being cleaned during field study.

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Figure 11. Jeep being cleaned during field study (hot, high-pressure washer in background).

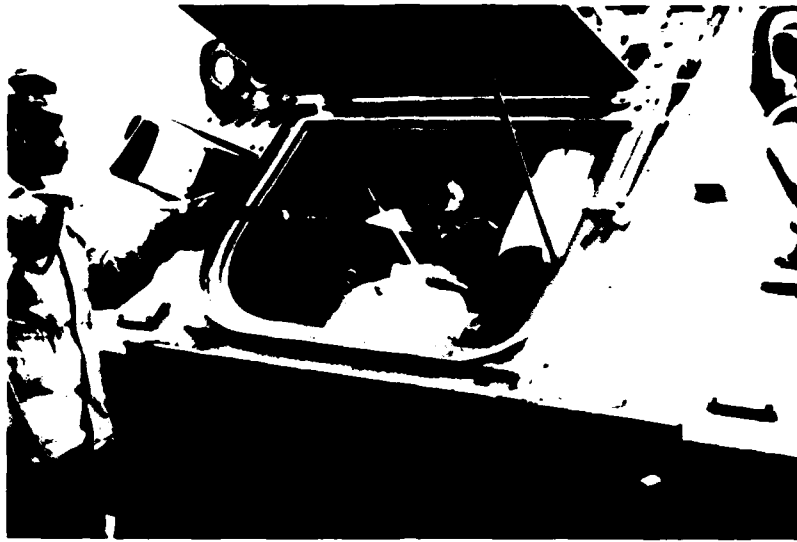pit using the 500-psi (3445-kPa) washer adjusted through its complete range of temperature settings: 50, 110, 130, 150, 170, and 190°F (10, 43, 54, 65, 77, and 88°C). After this study was conducted, all machines were adjusted to 130°F (54°C) for the remaining field tests.

3 RESULTS AND ANALYSIS

Literature and Industry Survey

The findings of both the literature survey and industry survey were of little help in developing guidelines. The literature focused on damage caused by extremely high pressures in the range of 8000 to 10,000 psi (55 120 to 68 900 kPa) and therefore was not applicable to maintenance cleaning operations. The washer manufacturers and users surveyed had general guidelines for safe operating conditions; however, they had no concrete backing for their figures. They generally agreed that damage could be caused by high pressure water, but none could say at what pressures this damage would begin.

Theoretical Analysis

The theoretical analysis of potential damage from high pressure sprays concentrated on identifying the operating parameters that contribute to impact energy

on a unit area (see the appendix). Equations were developed and graphs generated which indicated the sensitivity of unit impact energy to the parameters of pressure, flow rate, spray angle, and distance.

The results of this analysis indicated that pressure had the greatest influence on impact energy, followed by distance, spray angle, and flow rate. Thermal energy was not considered by this study because its effect would depend on the material make-up and surface characteristics of the object being cleaned.

The theoretical analysis was useful in determining which parameters required the greatest study, but beyond this was of little practical value since the information could not be related to damage. Lab and field tests were needed to develop reliable guidelines for using hot, high-pressure water washers.

Laboratory Phase

The lab phase of this study allowed the collection of much data in a relatively short time. All six operating parameters were controlled in the lab such that the effect each one had on component damage could be assessed more accurately than would have been possible in the field. Of the four field-controllable parameters, pressure was generally the most critical, followed by spray angle, flow rate, and temperature. Damage was also influenced by the two parameters which were not field-controllable: distance the nozzle was held

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Input Seal Tests

Figure 12 shows the results obtained when final drive input seals were tested with different spray angles. The results of one pressure and temperature test are shown in Figure 13. Figure 12 indicates very strong correlations between spray angle and seal failure, and between distance and seal failure. The more dispersed the spray (the wider the spray angle), the less likely failure will occur at any given pressure. However, this effect is reduced as the nozzle is moved closer to the seal and the spray becomes more concentrated. The one inconsistency in the data is the 3-in. (76-mm) test using the 25-degree nozzle. One would expect seal failure at a lower pressure than with the 40-degree nozzle, not at a higher pressure as indicated. This is explained by the fact that the 25-degree nozzle, which was manufactured by a different company than the other nozzles, had a slightly wider spray pattern, as measured across the minor axis. Since this difference is not believed significant, studying each manufacturer's nozzles is not necessary. As long as the nozzles produce a fan-type spray pattern (considerably longer on the major axis than on the minor axis), the results should be similar to those found here.

Figure 13 illustrates the effect of temperature on seal failure. The relationship appears to be very weak and is probably insignificant. This figure also reillustrates the influence distance has on seal failure.

Radiator Hose Tests

The second major component tested was radiator hose. Researchers soon learned that the point at which damage occurs is not always well defined. While some components either pass or fail a test, hoses exhibit gradations of damage ranging from barely visible abrasions to catastrophic punctures. Therefore, the evaluation of damage becomes very subjective; researchers had to judge whether the service life of the component being tested would remain unchanged, be reduced, or end as a result of each test.

To help evaluate how the spray parameters of pressure, temperature, flow rate, nozzle angle, distance, and time affect damage to radiator hose, the display boards described in Chapter 2 were constructed. These boards were analyzed to produce the graphs shown in Figures 14 through 17. For these graphs, slight damage was defined as surface abrasions which probably would not reduce the life of the hose. Moderate damage

meant that the outer layer of rubber had been cut, but not the nylon reinforcing layer. This probably would lead to early, but not necessarily immediate, failure of the hose. Severe damage was defined as having occurred when the reinforcing layer had been torn. This would most likely lead to rapid failure if the hose were actually put into service. Within each of these categories there were degrees of damage, and there could be some overlap between categories, depending on the evaluators' judgment. Despite these limitations, however, the graphs adequately illustrate the test results.

Figure 14 shows the influence nozzle spray angle has on damage. In general, the wider the angle, the less damage to the hose at any given pressure, distance, flow rate, temperature, and exposure time. If minimizing damage were the only consideration, it would follow that the 40-degree nozzle is the best choice. However, wider sprays do not clean as well as narrower ones. During the lab study, it was determined that the 25-degree nozzle represents a good compromise between maximum cleaning effectiveness and minimum potential for damage.

Figure 15 illustrates the effect nozzle size, or flow rate, had on hose damage. Although some effect can be seen, it is not marked, as the vertical nature of the damage zones indicates. Because of this, the choice of flow rate can be based primarily on other factors, such as cleaning effectiveness, without significantly increasing the potential for damage.

Figure 16 shows the effect of water temperature on hose damage. As with flow rate, the influence is not strong. Based on these data alone, almost any temperature appears safe in the lower pressure ranges, and most temperatures above ambient appear slightly harmful at elevated pressures. It would be difficult to choose the best temperature without first considering cleaning effectiveness and safety. These are discussed on pp 21 and 22.

Figure 17 shows how the distance maintained between the nozzle and hose influences damage. A rather dramatic increase in damage occurs when this distance is reduced, especially at elevated pressures. Also of interest is the extreme sensitivity to distance. A decrease of only 1 in. (25.4 mm) can make the difference between no damage and some visible damage, or between slight damage and potentially catastrophic damage. Unfortunately, there are no commercially available guards which prevent the nozzle from coming too close to a part, and which do not hinder cleaning operations in confined work spaces.
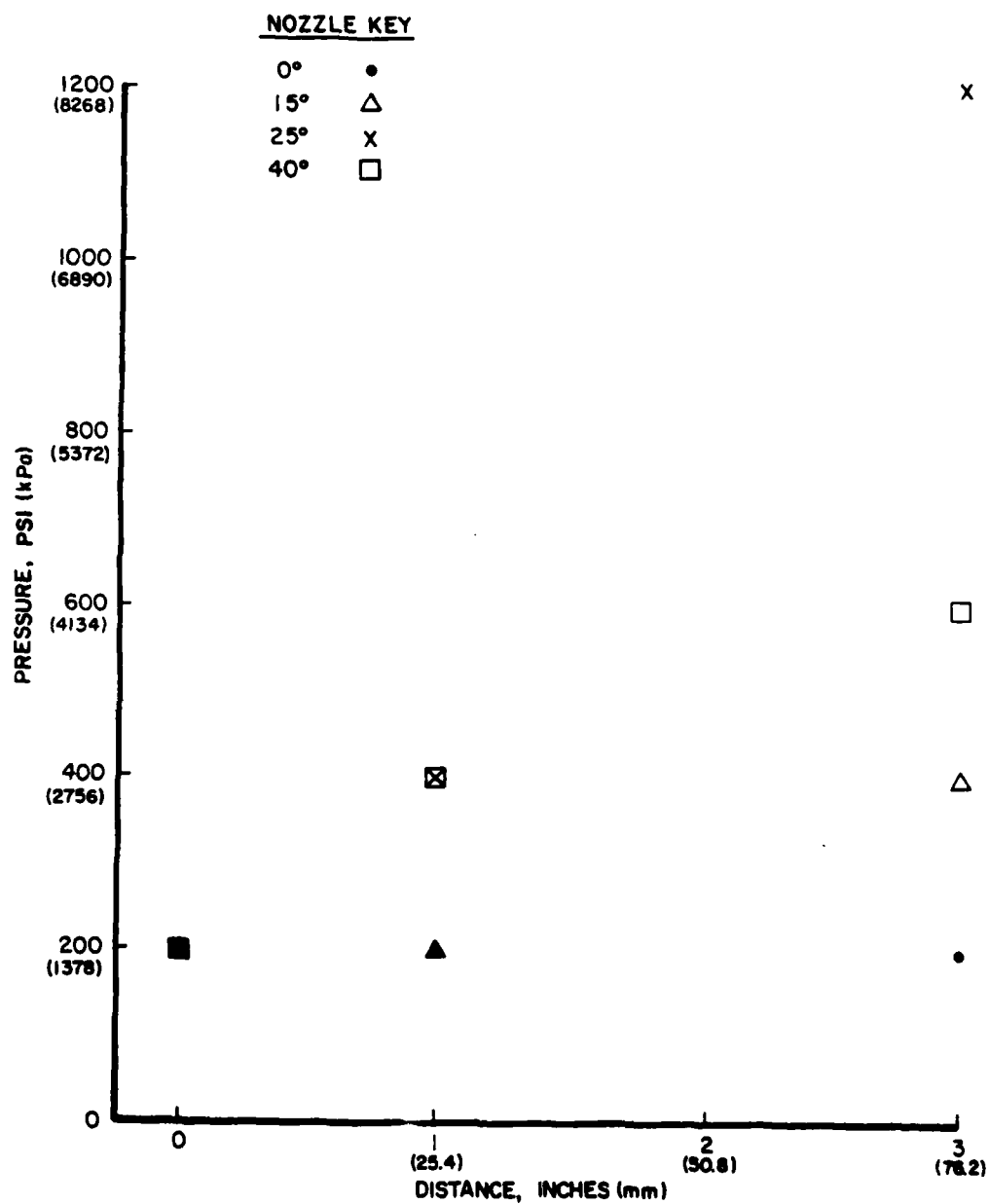
16

Figure 12. Final drive seal failures as a function of pressure, distance, and nozzle spray angle (No. 9 nozzles, 45°F [7.2°C] water, 10-second exposure times).
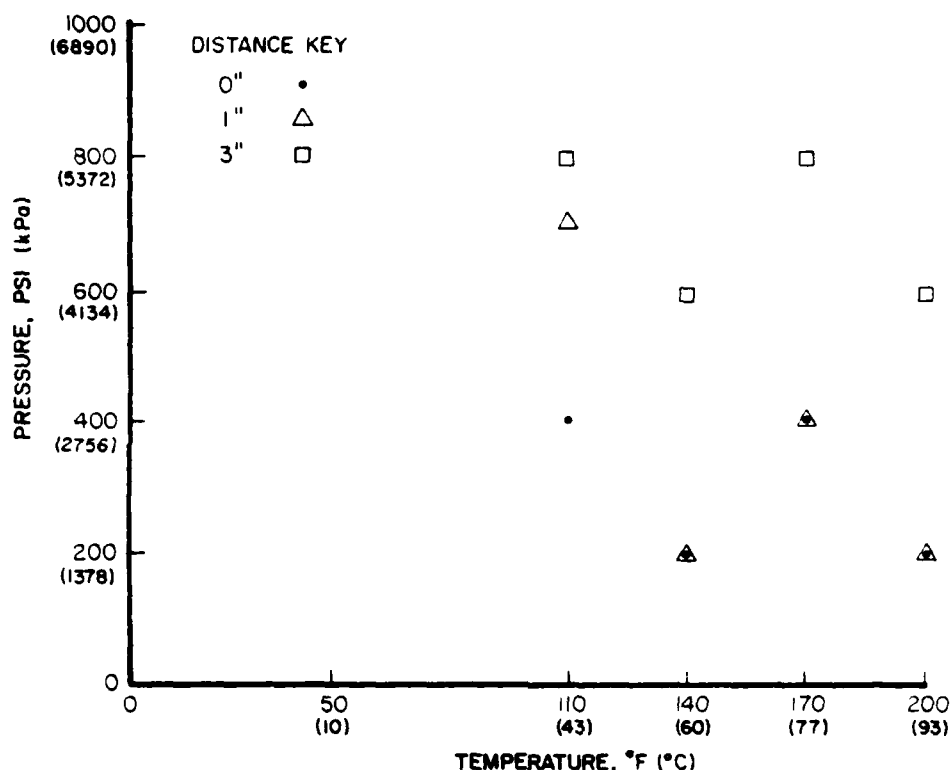
Figure 13. Final drive seal failures as a function of pressure, temperature, and distance (25-degree, No. 9 nozzle; 10-second exposure times).

In each of Figures 14 through 17, pressure is a variable. This means that to find the best settings for nozzle angle, flow rate, and temperature, the most appropriate pressure setting had to be determined first. This was done with the field tests discussed on pp 21 and 22.

The potential for damage cannot be eliminated because distance and exposure time cannot be controlled in the field, and because components such as radiator hose exhibit degrees of damage rather than having a threshold point for failure. Even at very conservative settings, the nozzle can be held close to a hose long enough to cause damage. Thus, there must be some compromise between reduced risk of damage and increased cleaning effectiveness. Even after this decision is made, the soldier operating the washer must be careful when cleaning near sensitive components.

Electrical Connector Tests

The third major component studied was cannon-plug electrical connectors. It was found that both new and used electrical connectors failed at very low pressures, even at distances greater than 3 in. (76 mm). At a distance of 6 in. (152 mm), failure occurred at pres-

sures as low as 200 psi (1380 kPa); and even at 1 ft (305 mm) one connector failed at 400 psi (2760 kPa). Although these tests represent a worst-case situation, with water sprays being concentrated on the connectors for a full 5 seconds, this could occur in the field. It appears that cannon-plug electrical connectors simply were not designed to withstand direct application of pressurized water sprays. Additional testing showed that these connectors can withstand applications of low-pressure water (50-psi [345-kPa] city water pressure) even at high velocity and point blank range.

Tests of Other Components

CERL also studied several other components. Not all of these were tested as thoroughly as the three already discussed; nonetheless, the test results expanded the findings of this study and therefore deserve consideration.

V-belting was studied along with radiator hose in the display board tests. Figures 4 through 8 show samples of V-belt mounted directly above radiator hose samples which have been subjected to identical sprays. These tests indicated that, in general, V-belts are

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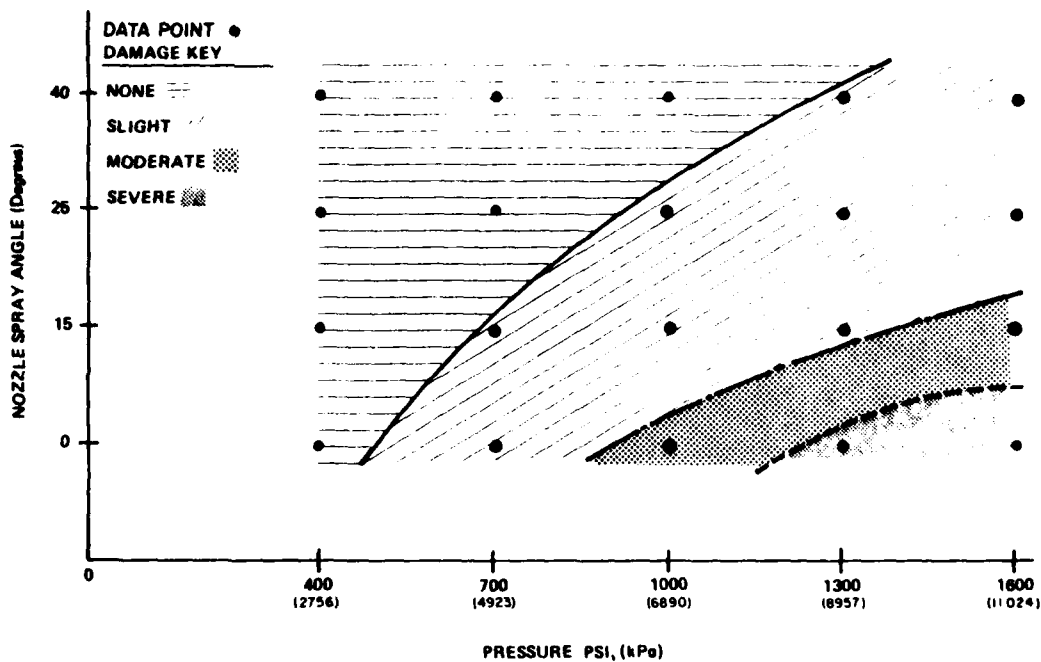
Figure 14. Damage to radiator hose as a function of nozzle spray angle and pressure (45°F [7°C] water, 3-in. [76.2-mm] distance, No. 9 nozzle, 5-second exposures).
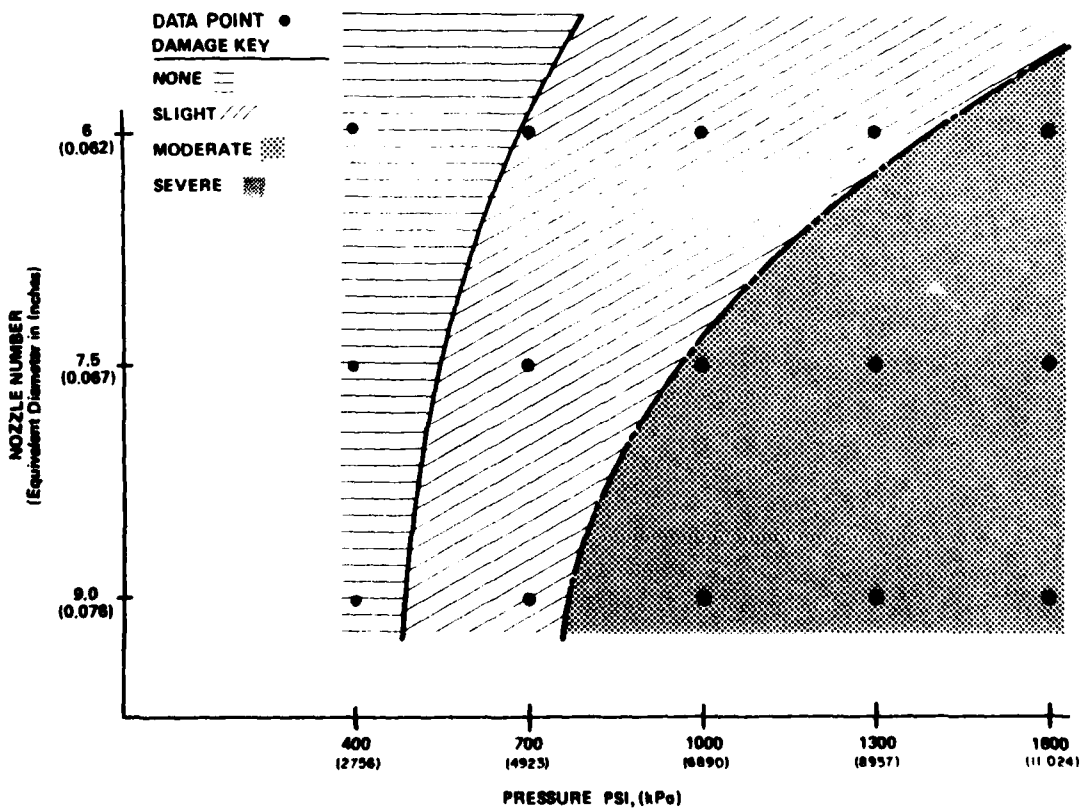
Figure 15. Damage to radiator hose as a function of nozzle size and pressure (45°F [7°C] water, 1-in. [25.4-mm] distance, 25-degree nozzle angle, 5-second exposures).

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Figure 16. Damage to radiator hose as a function of pressure and temperature (0-in. distance; 25-degree, No. 9 nozzle; 5-second exposures).

Figure 17. Damage to radiator hose as a function of distance and pressure (130°F [54°C]; 25-degree, No. 9 nozzle; 5-second exposures).

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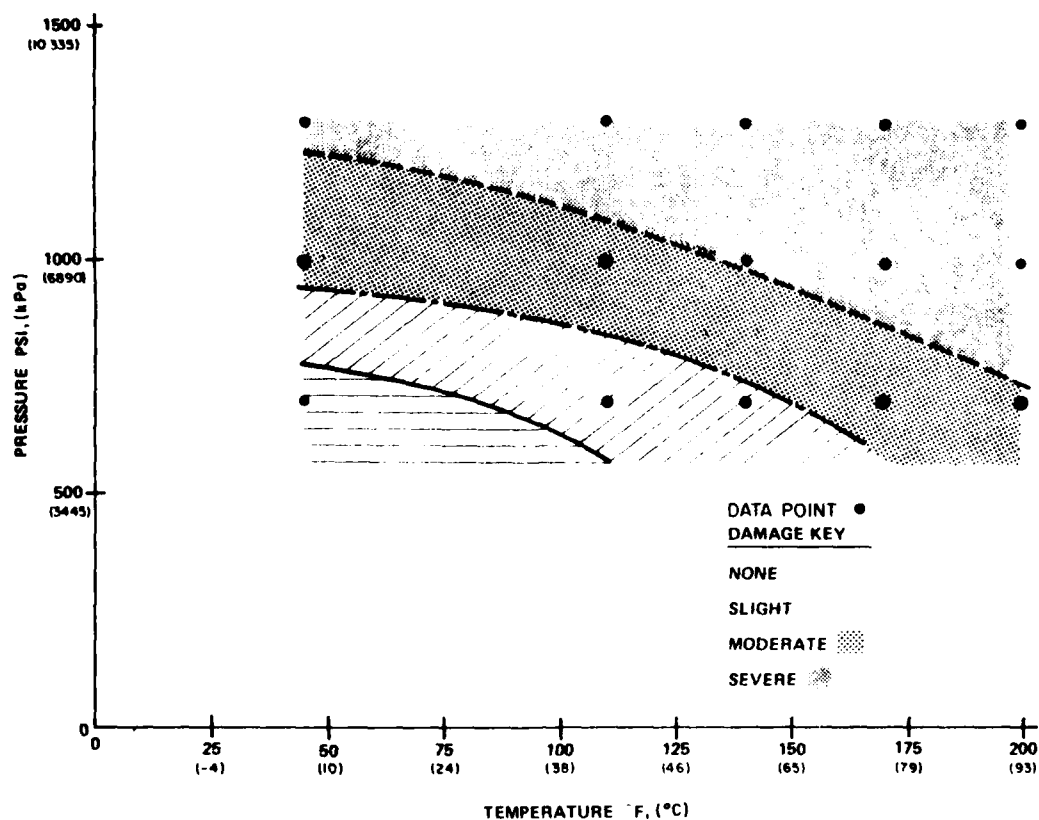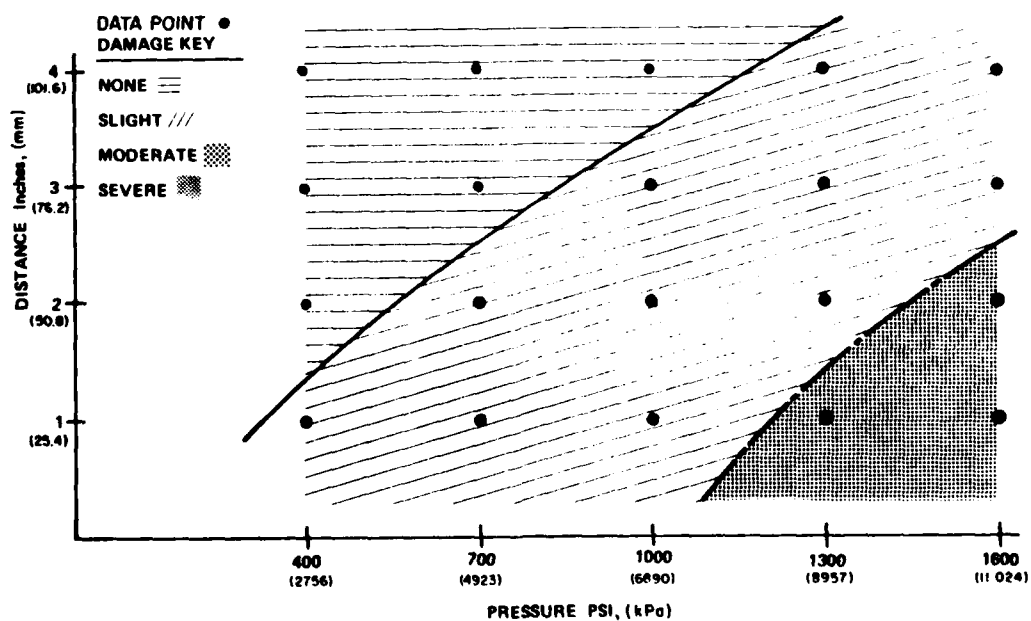slightly more susceptible to damage than radiator hose. This is probably because of the difference between a flat surface, which reflects the spray, and a rounded surface, which diverts the spray. Another factor could be differences in the strength and resiliency of the components' materials of construction.

Spider joints, or universal joints, were briefly tested; these withstood the highest pressure used, 2800 psi (19 290 kPa). This is not altogether surprising, considering that each bearing cap has a double rubber seal and an overlapping metal seal protector.

Spark plug to spark plug lead connectors withstood pressures to 2200 psi (15 160 kPa). Unlike cannon plugs, these connectors have rubber seals, which greatly increase their resistance to intrusion of foreign matter.

CERL also tested hydraulic hose and a second variety of radiator hose used on some Army vehicles. The hydraulic hose responded much like the V-belts, showing early signs of slight damage but not being severely damaged until fairly high pressures were reached. The second variety of radiator hose tested seemed slightly more sensitive than the first, although not significantly so. Softer rubber in the outer layer and a rougher surface could account for the difference.

Tie-rod ball joint boots were tested; these showed signs of damage at 600 psi (4135 kPa) and 1-in. (25-mm)

distance, and failed at 600 psi (4135 kPa) point blank. Pressures as high as 1200 psi (8270 kPa) caused only moderate damage when a 3-in. (76-mm) distance was maintained.

Field Phase

As explained in Chapter 2, the field phase of this study was conducted to evaluate cleaning effectiveness and operator safety. Although quantitative data were collected to evaluate cleaning effectiveness, qualitative observations were of greater value. This was a result of variations beyond the control of the study, such as operator efficiency and relative dirtiness of the vehicles.

Table 1 lists the water and time needed to clean various vehicles using the 500 and 1500 psi (3445 and 10 335 kPa) pressure washers.* For both washers, there are wide variations in the times needed to clean any one vehicle type. This was caused by differences in the dirtiness of the vehicles, importance of vehicle cleanliness, the efficiency of the operators, and other factors. For example, if a vehicle were being cleaned for maintenance, a quick pass might suffice. If, on the other hand, the vehicle were being prepared for an inspector general's review, usually it would be cleaned thoroughly.

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*Information for the 1000-psi (6890-kPa) washer is unavailable because data sheets were stolen from the test site.

Table 1
Representative Field Data

| Vehicle Type | 500-psi (3445-kPa) Washer | | | | 1500-psi (10 335-kPa) Washer | | | |
	Date	Vehicle Number	Time, Min	Water, Gal (L)	Date	Vehicle Number	Time, Min	Water, Gal (L)
	4/21	A-21	8	26 (99)	4/22	CS-34	10	18 (68)
	4/22	C-4	98	233 (885)	4/22	CS-32	10	18 (68)
	4/22	A-48	40	90 (342)	4/27	CS-32	108	200 (760)
	4/22	A-4	1	2 (8)	4/27	CS-33	18	36 (137)
APC	4/22	A-50	25	46 (175)	4/27	CS-21	8	16 (61)
	4/26	C-32	13	27 (163)	4/27	CS-34	11	13 (49)
	4/26	C-51	9	18 (68)	4/28	B-46	10	20 (76)
	4/26	C-50	2	6 (23)	4/28	CS-34	10	17 (65)
	4/26	C-33	41	89 (338)	4/28	CS-5	83	154 (585)
	4/27	A-4	24	59 (224)				
	4/28	C-22	36	60 (228)				
	4/28	C-12	73	194 (741)				
Averages	--	--	30.8	70.8 (269)	--	--	29.8	54.7 (208)
Jeep	4/21	C-42	2	3 (11)	4/22	CS-82	2	6 (23)
	4/26	C-6	2	3 (11)	4/22	--	2	7 (27)
	4/28	C-40	5	8 (30)	4/26	CS-74	2	5 (19)
	4/29	A-40	2	4 (15)	4/29	CS-74	1	2 (8)
Averages	--	--	2.8	4.5 (17.1)		--	1.8	5.0 (19)

Averaging the data over a 2-week period reduced the effect of these variations on total wash time. When the averages are compared, there is very little difference between the two sets of data. This indicates that other factors involved in the cleaning operation are more important than the power of the machines. The slight variations in actual wash time from one machine to another are outweighed by the time required to prepare a vehicle for cleaning, to pass over all areas of the vehicle, and to reassemble the vehicle after cleaning. As long as the washers can clean effectively, the person using them is the determining factor.

Qualitative observations suggested that the 1000-psi (6890-kPa) washer removed dirt and grease more effectively than the 500-psi (3445-kPa) unit. The 1500-psi (10 335-kPa) washer was perhaps slightly more effective than the 1000-psi (6890-kPa) model, but not significantly so. One disadvantage of the higher pressure machines was an increase in backspray when cleaning in corners. Troop response was favorable to all three machines; however, some using the 500-psi (3445-kPa) washer felt it would do a better job if set at a higher temperature. A few soldiers complained about backspray while using the 1500-psi (10 335-kPa) washer, but felt it did an adequate job of cleaning. There were no complaints about the 1000-psi (6890-kPa) unit.

The results of the temperature study were also qualitative. Oily dirt was removed using the 500-psi (3445-kPa) unit set at temperatures ranging from 50 to 190°F (10 to 88°C). Noticeable improvement in cleaning effectiveness was observed when the temperature was increased from 110 to 130°F (43 to 54°C); higher temperatures offered only slight improvements. In addition, fogging increased at temperatures above 130°F (54°C); this obscured the operator's view of the work area.

Operator safety was of concern throughout the field test. It was obvious from the start that the higher the pressure and temperature of operation, the more hazardous a washer would be, but some basis for setting reasonable limits was needed. Only once during this study was a soldier actually injured while using a pressure washer. While attempting to wash his hands with the 1500-psi (10 335-kPa) unit, he cut his thumb with the force of the spray. Also, the excessive backspray at pressures above 1000 psi (6890 kPa) is a potential eye hazard. As for temperature limitations, 130°F (54°C) appears to be reasonable. This results in a wand temperature just below 120°F (49°C), which is approximately the pain threshold for most people. Thus, if any troops accidentally touch the metal parts of the wand, they should be able to change their grip without jumping or dropping the wand.

Although damage was not a main concern of the field study, inspections were made before and after each washing in an attempt to identify potential problem areas. No damage was observed with the 500-psi (3445-kPa) washer. Only one incident occurred with the 1000-psi (6890-kPa) washer: a V-belt was slightly damaged. There were two separate incidents with the 1500-psi (10 335-kPa) washer. One involved moderate damage to a hydraulic hose, the other slight damage to a spare tire. During the field study, two electrical connectors were inspected before and after the cleaning operations, one with the 1000-psi (6890-kPa) washer and the other with the 1500-psi (10 355-kPa) washer. In both cases the connectors were dry inside, even though cleaning had been done nearby.

Final Laboratory Tests

When the field tests had been completed, the results from both the lab and field were combined to determine optimum settings for washer operation. Once an effective pressure was decided on, the other parameters were chosen. Using these settings, CERL ran one final lab test similar to the display board tests already described. The summary board in Figure 8 was generated by this test.

The pressure was set to 800 psi (5510 kPa) and the temperature to 130°F (54°C); the nozzle used was a 25-degree, No. 9, which produced a flow rate of 3.5 gpm (13.2 L/min). Samples of radiator hose and V-belt were subjected to sprays at various distances for various lengths of time. The results of this summary test are shown in Figure 18. As the figure indicates, washers set to these settings still can cause damage if the nozzle is held at close range for an extended time.

Although close range and long exposure time are always possible under field conditions, observations indicated that troops tended to hold the nozzle at a fairly safe distance in order to achieve good coverage, and to keep the nozzle moving to get the job done. This is further supported by the fact that very little damage occurred in the field, even with the 1500-psi (10 335-kPa) washer.

4 CONCLUSIONS AND RECOMMENDATIONS

From the results of the lab phase of this study, it can be concluded that damage from hot, high-pressure
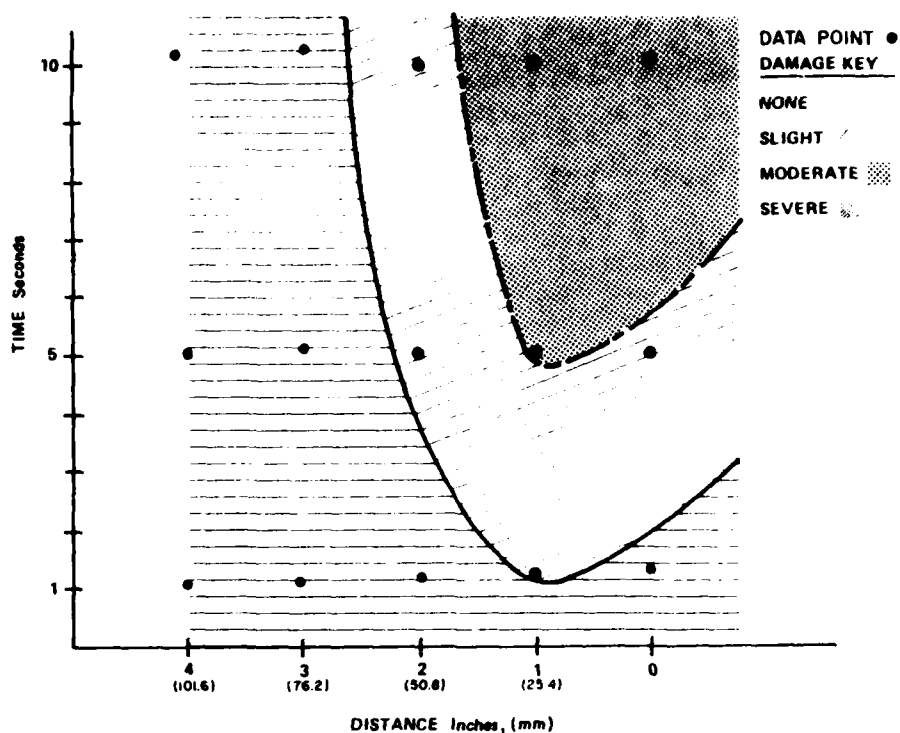
Figure 18. Damage to radiator hose as a function of time and distance at recommended settings of 800 psi (5512 kPa), 130°F (54°C), 25-degree nozzle, 3.5 gpm (13.2 L/min).

water does not exhibit threshold characteristics. There are no absolutely safe operational settings below which damage cannot occur and above which it will always occur. Rather, varying degrees of damage result, depending on water pressure, temperature, flow rate, spray angle, distance between nozzle and the component being sprayed, and time of exposure. As each of these parameters is changed, the amount of damage which results also changes.

From the results of the field phase of this study, it can be concluded that the washer's pressure and temperature—above the minimums of 500 psi (3445 kPa) and 110°F (43°C) used in this study—ha° little effect on the time required to clean any particular vehicle. Other factors, such as vehicle preparation and operator efficiency, contribute more to total wash time than does the effectiveness of the washer. Pressures above 1000 psi (6890 kPa) and temperatures above 130°F (54°C) are hazardous: at close range, the spray can cause cuts; backspray from vehicles can get into the eyes; and unshielded parts of the wand can cause burns.

To achieve effective maintenance cleaning and to lessen the risk of damage to Army vehicles and injury to Army personnel, it is recommended that hot, high-

pressure washers used for maintenance cleaning be adjusted to a pressure of 800 psi (3510 kPa) and a temperature of 130°F (54°C) (both measured at machine output), and be equipped with a 25-degree nozzle sized to provide a flow rate of about 3.5 gpm (13.2 L/min). It must be emphasized that even at these recommended settings, some risk of damage still exists; therefore, operators must be trained to be careful when cleaning near sensitive items such as oil seals and electrical connectors. Distances of 6 in. (152 mm) or more should be maintained between the nozzle and the part being cleaned, and the spray should not be concentrated on any one spot for more than 5 seconds.

5 DIRECTIONS FOR FUTURE WORK

This chapter presents recommendations for future work on sensitive components; new materials research; rustproofing; maintenance manuals; washer development; nuclear, biological, and chemical (NBC) decontamination; and non-developmental vehicles.

Through the work already completed, certain components have been identified as especially sensitive

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to water sprays: electrical connectors and, to a lesser extent, oil seals. At virtually all washing pressures, water might enter electrical connectors. These devices have been designed to seal out dirt and moisture, but not pressurized water sprays.

Oil seals will withstand greater spray pressures than will electrical connectors: however, seals have not been designed to withstand pressures as high as those required for effective maintenance cleaning. Their function is primarily to retain oil within the gearbox or engine, and only secondarily to prevent dirt or moisture from entering.

Rather than accounting for these unprotected designs by adjusting cleaning equipment or techniques, a more direct (proactive) approach would be to redesign the components so that they can withstand the spray pressures necessary for good cleaning. Electrical connectors could be fitted with internal seals or external protective covers. Oil seals could be fitted with protective shields or designed with a double lip to seal in both directions.

Once sensitive components are redesigned and tested, implementing them could take three different approaches:

1. New vehicles being constructed, or used ones being rebuilt, could be fitted with the improved components.

2. A retrofit program could be started so that all vehicles could be converted on a schedule.

3. The new components could be introduced gradually as old ones wear out and have to be replaced.

An additional benefit of taking a redesign approach is that the improved components would provide more reliable service under adverse conditions.

The new generation of Army vehicles represents a dramatic departure from current designs. New materials, such as fiberglass, high-impact plastics, and polymerized paints are being used more often. Before any new material is accepted for production vehicles, one important acceptance test should be the capability to withstand hot, high-pressure water cleaning. The findings of these tests could result in nonacceptance of the material, a change in recommended cleaning equipment, or perhaps the issuance of special cleaning procedures for certain components.

Currently underway at TACOM is an extensive rustproofing program to reduce corrosion both on current vehicles and on those being developed. For current generation, or retrofit, rustproofing oil-based coatings are applied to vehicle chassis. Future generation vehicles will resist corrosion through the use of double galvanized steel and fiberglass.

An important area of concern is how these coatings and materials will withstand repeated cleaning, especially at elevated pressures and temperatures. It would be best to do this research before the systems are used.

Proper maintenance cleaning is essential to any maintenance program. Cleaning of each vehicle should be addressed directly and specifically in a separate section of each maintenance manual. Some manuals address cleaning in several sections. Often, instructions are given in very general terms. For example, a manual might say, "avoid high pressure water in this area," without defining how much pressure is too high. Supplying troops with clear, concise cleaning instructions for each vehicle could be an important step in improving cleaning operations and reducing damage to Army vehicles.

The Army has maintenance operations which require unique cleaning equipment and procedures. To meet its requirements, the Army should begin developing equipment rather than accepting commercially available washers. For example, a field-operational, highly durable washer that can be air-dropped is clearly needed. Another useful feature might be a pressure adjustment to allow for various cleaning requirements.

A detailed study might reveal that the Army needs a "family" of washers rather than a single unit. Each washer could then be tailored to the specific needs of the shop or unit it will service.

An offshoot of this work could be the development of washer accessories, such as sandblaster attachments for paint and rust removal, or user-acceptable nozzle guards.

An overall analysis of the Army's maintenance cleaning needs might identify a requirement for a waterless cleaning system, such as a low-pressure solvent washer. This equipment might be developed through a basic research effort.

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Hot, high-pressure washers could be very effective for decontaminating Army vehicles in an NBC warfare environment. A study could identify the operational settings needed for washers to remove various contaminants.

Nondevelopmental vehicles (such as the 5300 Chevrolet Blazers and trucks recently procured by the Army) are not designed to typical Army "rugged" specifications. Guidance is needed for proper cleaning of these vehicles.

APPENDIX:
THEORETICAL ANALYSIS OF IMPACT

Impact can be simply described for a spray as the total force of a mass of water or other fluid on a given surface. The following general formula further refines this definition.

Impact = Mass per unit time X spray velocity [Eq A1]

Several variables affect impact of a spray. Among these are flow rate, spray angle, operating pressure, concentration of the spray, particle size, and air friction.

All these variables influence either the mass per unit time or the velocity, which in turn affects the impact. Flow rate is essentially the mass per unit time and is given in terms such as gallons per minute. Pressure affects both velocity of the water stream and mass per unit time. Particle size affects the velocity in that smaller particles lose velocity due to air friction more rapidly than do larger particles. Air friction affects the velocity and is a variable in the sense that it depends on the velocity of the particle. For example, air friction has a greater effect on small particles such as finely atomized sprays; therefore, the velocity of the particles should be slower at any given distance from the nozzle than it would be for larger water particle sizes exiting from larger nozzles.

The type of nozzle, or spray pattern, also influences impact because spray concentration, distribution, and velocity are affected.

Total impact of the nozzle must be distinguished from impact per unit area; the latter is more important in vehicle washing. The total impact of two nozzles may be the same, but the impact per unit area can be entirely different. Spray angle and the concentration of the spray affect impact per unit area, but not total impact. The smaller the spray angle and the more concentrated the spray pattern, the higher the impact per unit area. Another factor which directly affects the impact per unit area is the distribution of the spray.

The following discussion defines the terms and describes the formulas used in CERL's theoretical analysis of impact.

Theoretical Total Impact

For any given nozzle, theoretical total impact is the total impact, neglecting all losses, that an equivalent straight stream nozzle would have when operating at the same pressure and with the same flow rate as the given nozzle. An equivalent straight stream or straight stream nozzle forces water out with no angle of spray (0 degrees). Theoretically, this exerts maximum impact per unit area.

The impact formula used in calculations involved with the charts and graphs discussed below is:

Theoretical total impact (I) $= 0.0526 \, Q \sqrt{P}$ [Eq A2]

where: Q = the flow of water in gallons per minute

$\sqrt{P}$ = the square root of the operating pressure of the nozzle in pounds per square inch.

The constant and the formula are derived as follows

I = force exerted by the water striking the surface being sprayed in pounds

W = weight of water striking the surface in a unit of time (lb/sec)

V = liquid velocity in feet per second

g = acceleration due to gravity equal to 32.2 ft/sec²

V can also be in the form $\sqrt{2gh}$, where h is the head pressure in feet.

Therefore $V = \sqrt{2(32.2 \, \text{ft/sec}^2)(h)}$; h also can be defined as 144 P/d where P is the pressure in pounds per square inch, and d is the density of the liquid in pounds per cubic foot. For water at 70°F (21°C) this value is 62.3 lb/cu ft. Therefore:

$$V = \sqrt{288g \frac{P}{d}}$$ [Eq A3]

W expressed in terms of Q becomes:

$$W = \frac{Q \, (8.34 \, \text{lb/gal})}{60 \, \text{sec/min}} = 0.139 \, Q \, \text{lb/sec}$$ [Eq A4]

where 8.34 is the weight of 1 gal (3.8 L) of water.

$$V = \sqrt{288g \frac{P}{d}}$$

$$= \sqrt{288(32.2 \, \text{ft/sec}^2)(P \, \text{lb/sq in.})/(62.3 \, \text{lb/cu ft})}$$

$$= 12.2 \sqrt{P} \, \text{ft/sec}$$

Given: I = WV/g

$$I = \frac{(0.139 \, Q \, \text{lb/sec})(12.2 \sqrt{P} \, \text{ft/sec})}{32.2 \, \text{ft/sec}^2}$$

therefore: I $= 0.0526 \, Q \sqrt{P} \, \text{lb}$ [Eq A5]

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Impact Per Square Inch for Straight Stream Nozzles

Impact per square inch = 1.9 P   [Eq A6]

where P is the spraying pressure in pounds per square inch. This is the impact per square inch of any size straight stream nozzle at a distance of 12 in. (0.3 m).

Total Impact Efficiency

Total impact efficiency is the ratio of the actual total impact to the theoretical total impact:

$$\text{Total impact efficiency} = \frac{\text{Actual total impact}}{\text{Theoretical total impact}} \times 100 \qquad [\text{Eq A7}]$$

Percent Impact per Square Inch of the Theoretical Total Impact

This is the ratio of actual impact per square inch, assuming uniform distribution, to the theoretical total impact:

$$\text{Percent impact per square inch} = \frac{\text{Actual impact per square inch}}{\text{Theoretical total impact}} \times 100 \qquad [\text{Eq A8}]$$

Impact per Square Inch

Impact per square inch is a quantity derived from other information as follows:

1. First solve for theoretical total impact (I_t) using $I_t = 0.0526\, Q\, \sqrt{P}$ with given flow rate and pressure.

2. From Table A1 obtain the value for percent per square inch of the theoretical total impact. Then multiply that value by the total theoretical impact found in step 1.

Note: These values apply to 12-in. (0.3-m) distances from the nozzle and assumption of water being sprayed at 70°F (21°C).

Table A1 is helpful in determining various values involving impact. Five different types of nozzles are described. This table generally discusses a few of the quantities involved.

Flat spray nozzles are best for high pressure washing. They are easy to use and have the impact properties needed to remove dirt and grease.

Graphs and calculations were developed to understand more fully the concept of impact and its relationships. Figure A1 shows what happens to impact

as the flow rate increases with the pressure held constant. This is strictly theoretical, according to Eq A2. It is easy to see the direct linear correlation between I and Q. Figure A2 shows an increased scale of the same situation and indicates the more appropriate range of values which would be involved in vehicle washing.

Figure A3 indicates the effect of increasing pressure on total theoretical impact, again according to Eq A2, with the flow rate being held constant. This shows that impact varies with the square root of pressure in a parabolic curve. An expanded scale version of the situation is presented in Figure A4, again indicating the probable usage range in vehicle washing.

Eq A2 is based on the use of 70°F (21°C) water: Figure A5 shows what happens to the density of water as the temperature increases or decreases. Figure A6 contains temperature correction factors for total theoretical impact. The 70°F (21°C) standard is used, and factors are presented which show what effect changing temperature would have on the total theoretical impact. It can easily be seen that temperature has little effect on total theoretical impact.

Figures A7 and A8 show total theoretical impact in pounds per square inch versus the spray angle of the nozzle with three different flow rates and different operating pressures. Figure A7 graphs Spraying System Co. Veejet sprays, and Figure A8, Flatjet sprays; for both, CERL used a 12-in. (0.3-m) distance from the nozzle to the surface. The general indication is that a smaller spray angle results in a higher impact.

The diameter of the nozzle and the shape of its internal construction also affect the capacity or flow rate. Figure A9 illustrates the flow rate for a nozzle with a 40-degree spray angle; the actual capacity is shown for different orifice diameters and pressures. The predicted capacities for several other nozzles and the ratio of actual to predicted also were calculated. That ratio seems to be consistently around 0.90 (see Figure A10), indicating that the nozzle loses about 10 percent of its capacity through internal friction. The formula used for predicting capacity was:

$$Q = AV \qquad [\text{Eq A9}]$$

$A = \pi r^2$, with r in feet

$V = 12.2 \sqrt{P}$ ft/sec, as shown previously

$$Q = \pi r^2 \, (\text{ft})^2 \, 12.2 \sqrt{P} \, \frac{\text{ft}}{\text{sec}} \times \frac{60\,\text{sec}}{\text{min}} \times \frac{7.48\,\text{gal}}{1\,\text{cu ft}}$$

$$= 17{,}201 \, r^2 \sqrt{P} \text{ gallons per minute.}$$

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As pressure increases, coverage does not necessarily increase for a given distance from nozzle to surface. Width usually increases while thickness decreases, with total surface area increasing up to 20 psi (138 kPa), then decreasing. The surface area covered increases as the distance from nozzle to object increases. No general equation will produce consistent results because of the large number of variables involved. Experimental data are required.

For a general indication of the increased impact per square inch caused by a shorter distance from nozzle to surface, the following relationship was used.

Assume a spray pattern in the shape of a rectangular pyramid, and consider the nozzle a point source:

α = major nozzle spray angle in degrees

β = minor nozzle spray angle in degrees

x = distance from nozzle to surface.

Then the surface area covered could be represented as a rectangle of dimensions:

$$2x \cdot \tan\frac{\alpha}{2} \text{ by } 2x \cdot \tan\frac{\beta}{2} \qquad \text{[Eq A10]}$$

neglecting any effects of flow or pressure. For example, given x as the distance from the nozzle to surface of 0.1, 0.5, 2.0, 4.0, 6.0, 12.0 in. (2.54, 12.7, 50.8, 101.6, 152.4, 304.8 mm).

α = 40 degrees
β = 10 degrees

The surface area covered would be, respectively, 0.00127, 0.03, 0.51, 2.04, 4.58, 18.34 sq in. (0.08, 1.95, 33.15, 132.6, 297.7, 1192 mm^2). And using 0.0526 Q $\sqrt{P}$ for theoretical impact with 5 gpm (30 × 10^{-5} m^3/sec) as Q and 500 psi (3445 kPa) as P, the resultant impact per square inch would be as follows:

X distance away, inches (mm)	Impact per square inch, psi (kPa)
0.1 (2.54)	4616 (31 804)
0.5 (12.7)	667 (4596)
2 (50.8)	11.53 (79.4)
4 (101.6)	2.88 (19.8)
6 (152.4)	1.28 (8.8)
12 (304.8)	0.32 (2.2)

This shows the tremendous change in impact per square inch with varying distances from nozzle to the surface to be sprayed. Caution is obviously called for because at point blank range these pressures can cut wood, strip paint, and injure people severely.

In summary, impact is affected by many parameters, some of which interact, eliminating the possibility of a single, all-inclusive equation for predictions. Pressure, flow rate, and nozzle spray angle are the major factors, with several others contributing to the overall effects.

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Table A1
Effect of Nozzle Type on Impact Energy
(From Spraying Systems Co., Drawing No. 5829)

| Nozzle	Nozzle Spray Angle (Degrees)	Total Impact Efficiency 12 in. (0.3 m) From Nozzle (Percent)	Percent Impact per Sq In. of the Theoretical Total Impact 12 in. (0.3 m) From Nozzle
Straight Stream Has high impact efficiency with only slight losses due to friction. No value is given for the percent impact per sq in. since this remains constant for all capacities, the pressure being constant.	0	96 to 99	See Eq A2 for impact per sq in. of any straight stream nozzle
Veejet Impact efficiency is high. The narrow angle spray will have the higher total impact efficiencies.	15 25 40 50 65 80	95 to 90	30 18 12 10 7 5
Flatjet The total impact efficiency is not as high as the Veejet because of friction losses due to the deflector surface. However, the spray is more concentrated, and the percent impact per sq in. is as high as the Veejet.	15 35 40 50	80 to 75	30 13 12 10
Fulljet Velocity efficiency varies with the spray angle; thus the impact efficiency also varies with the spray angle for this nozzle.	15 30 50 65 80 100	85 81 77 70 61 50	11.0 2.5 1.0 0.4 0.2 0.1
Whirljet Has the lowest total impact efficiency, but because of its concentration, the impact per sq in. will run just slightly higher than the Fulljet. The 60- to 80-degree spray angle range is given which covers most standard Whirljet nozzles.	60 to 80	50	2 to 1

Note: For nozzles spraying water at 70° F (21°C).
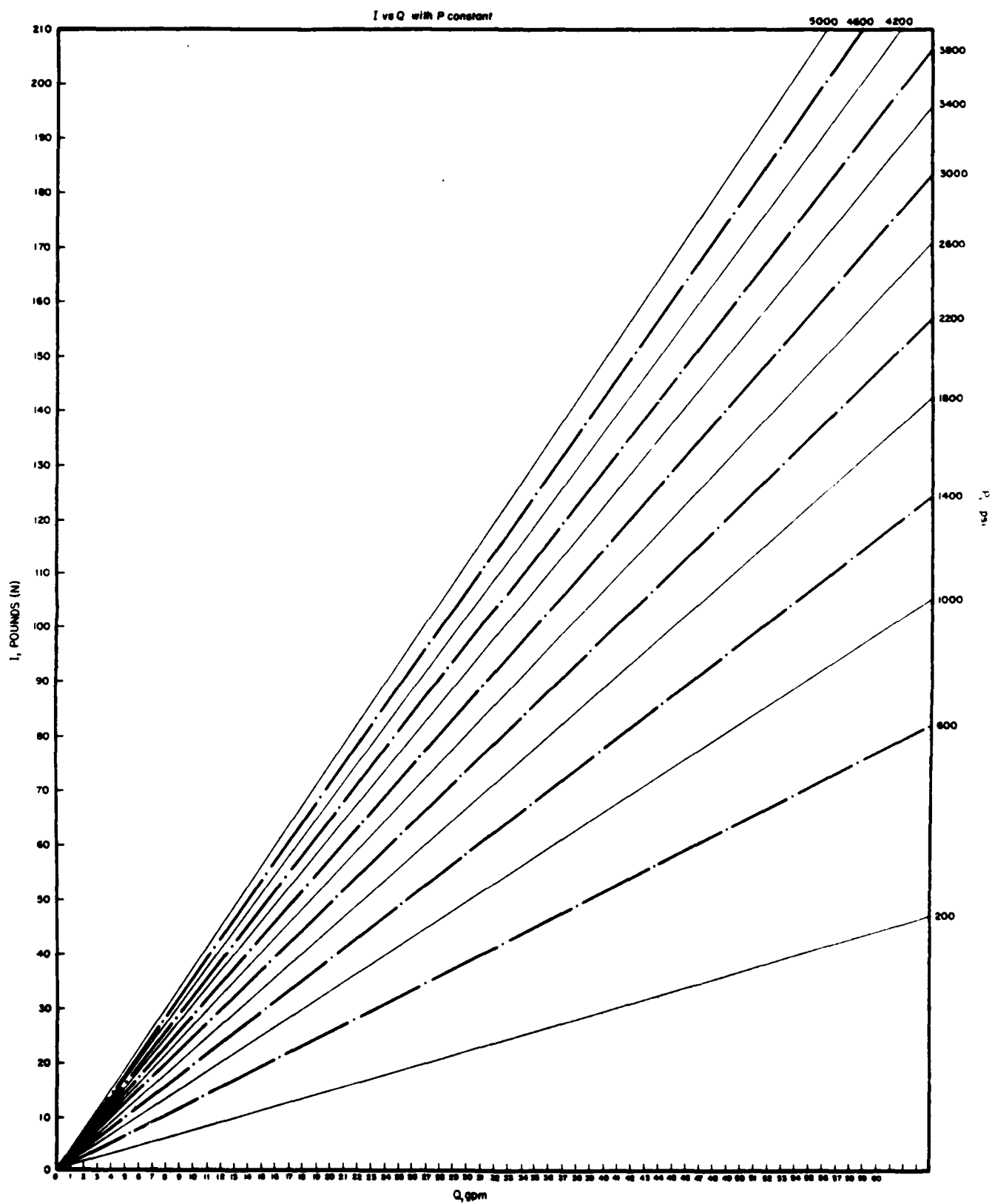
Figure A1. Theoretical total impact (metric conversion factors: 1 gpm = 6×10^{-5} m³/sec; 1 psi = 6.89 kPa; 1 pound force = 4.448 N).

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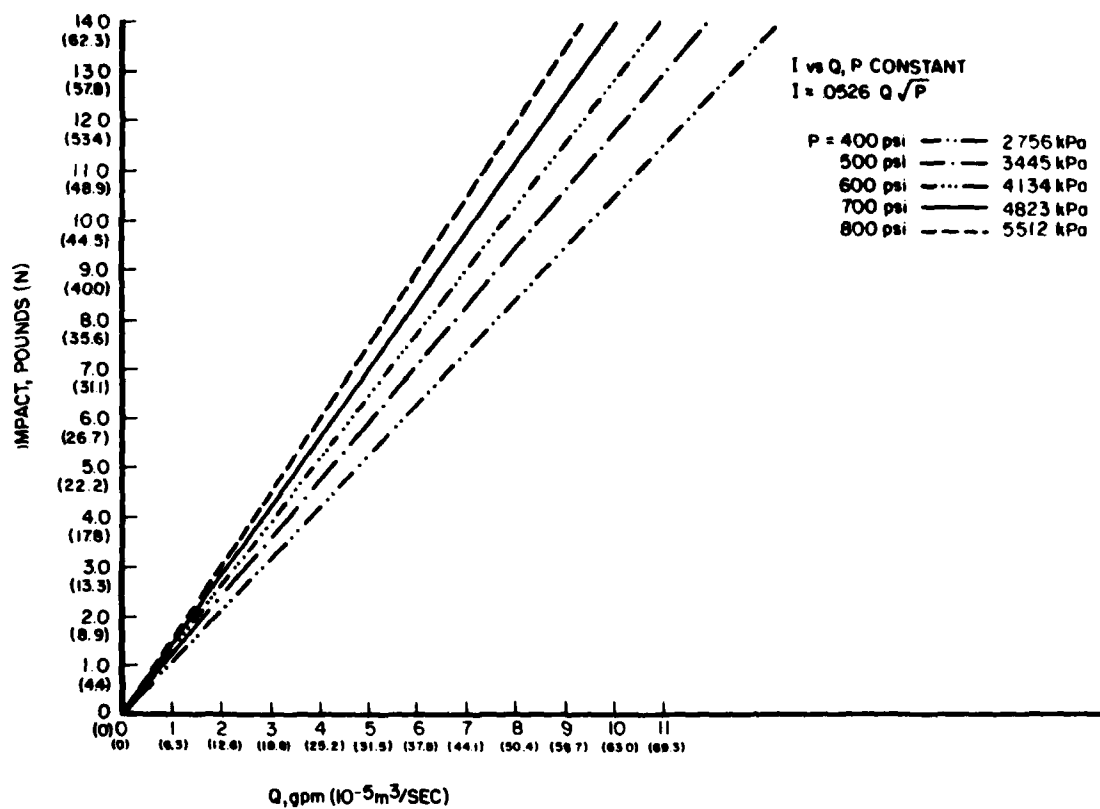**Figure A2.** Theoretical total impact; increased scale.
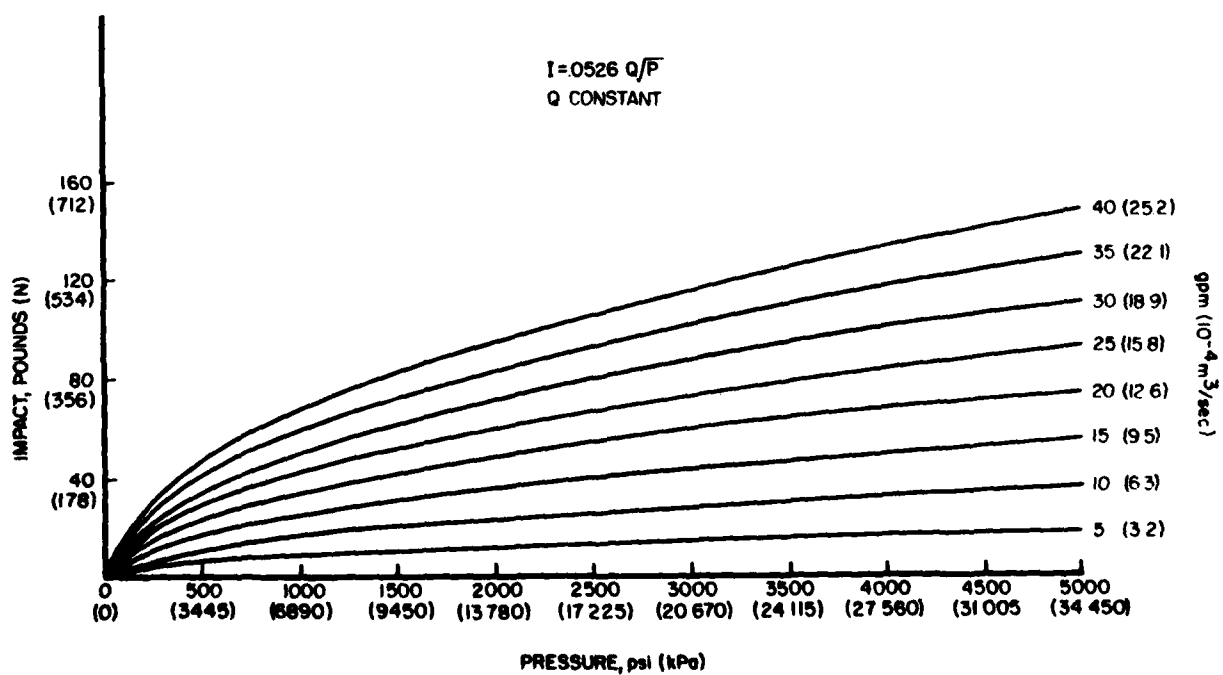

Figure A3. Impact versus pressure; Q constant.
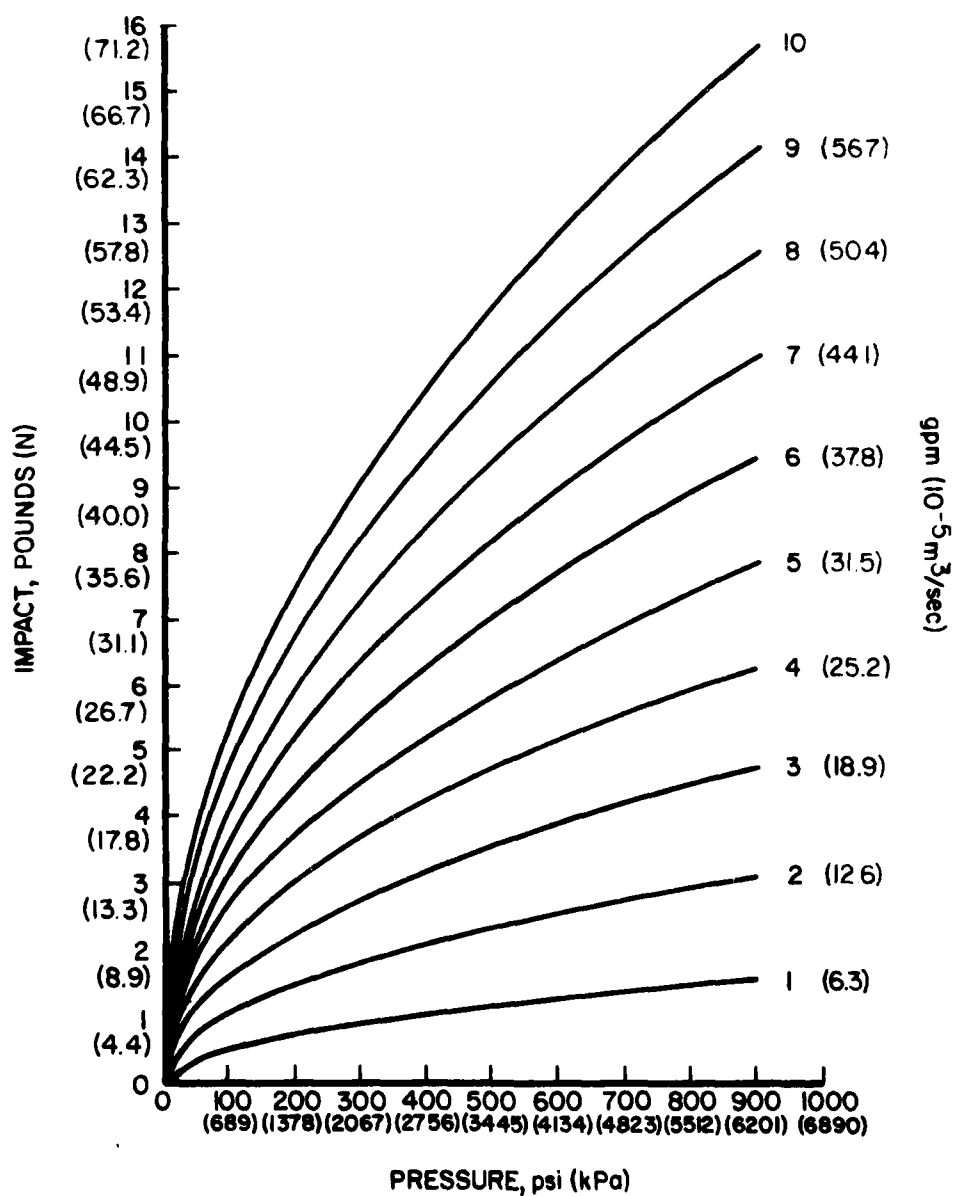
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$$I = .0526 \, Q \sqrt{P}$$
$$Q = \text{CONSTANT}$$

Figure A4. Impact versus pressure; expanded scale.

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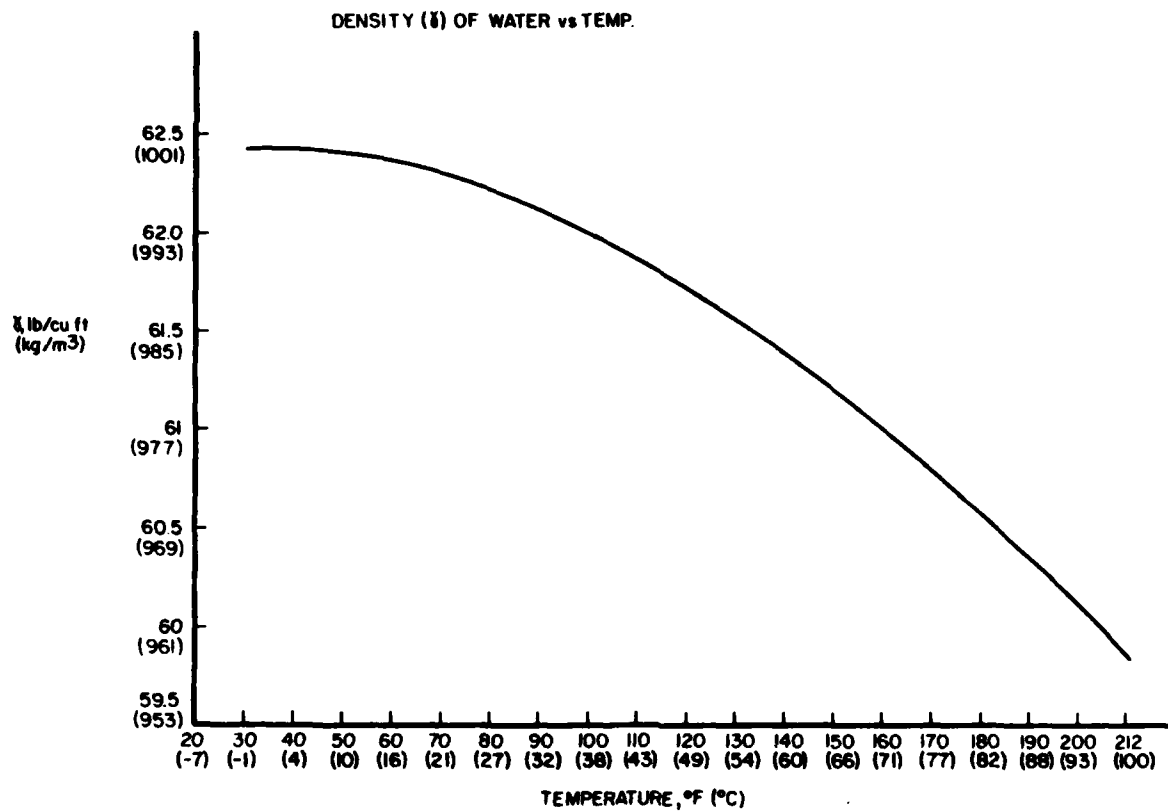
Figure A5. Density of water versus temperature.

EQ A2 IS BASED ON 70°F (21°C) WATER, δ = 62.3 lb/cu ft (997.4 kg/m³)

		C.F.
32°F	(0°C)	1.00
40	(4)	1.00
50	(10)	1.00
60	(16)	1.00
70	(21)	1.00
80	(27)	1.00
90	(32)	1.00
100	(38)	1.00
100	(43)	1.00
120	(49)	1.00
130	(54)	1.00
140	(60)	1.01
150	(66)	1.01
160	(71)	1.01
170	(77)	1.01
180	(82)	1.01
190	(88)	1.02
200	(93)	1.02
212	(100)	1.02

Figure A6. Water temperature correction factors (C.F.).

I/SQ IN. vs SPRAY ANGLE

Figure A7. Theoretical impact with Veejet spray (metric conversion factors: 1 psi = 6.89 kPa; 1 gpm = 6 × 10⁻⁵ m³/sec).

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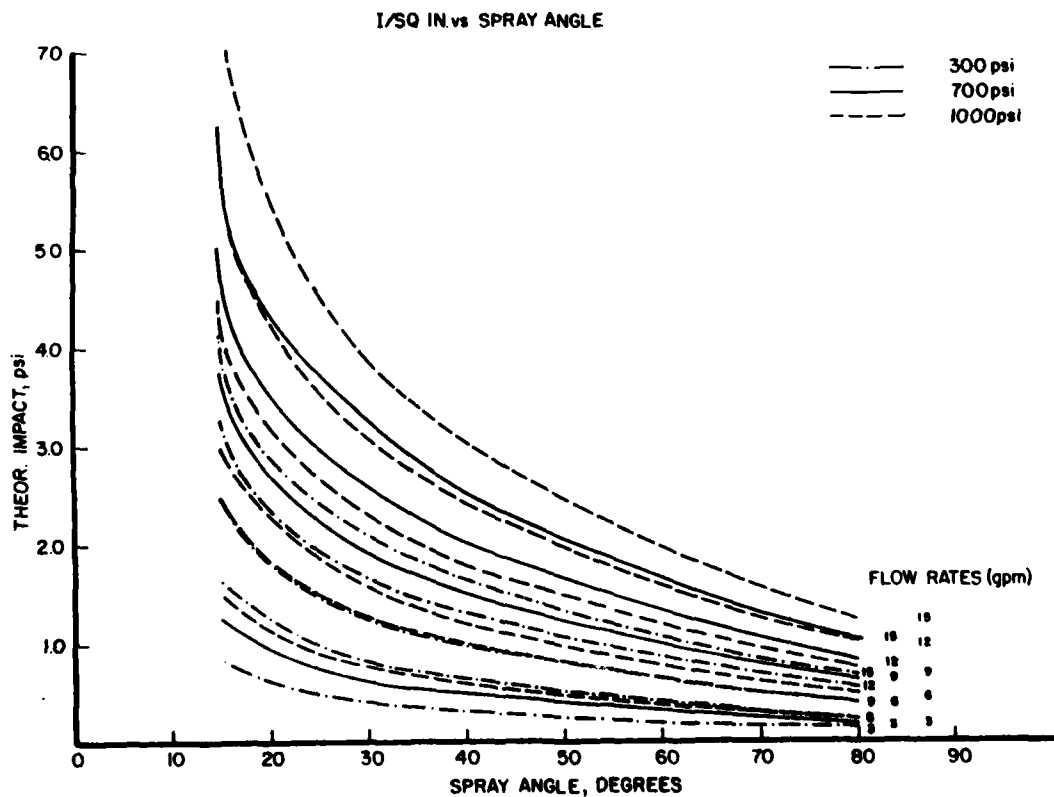
Figure A8. Theoretical impact with Flatjet spray.

Figure A9. Flow rate for nozzle with 40-degree spray angle (metric conversion factors: 1 in. = 25.4 mm; 1 gpm = 6×10^{-5} m^3/sec; 1 psi = 6.89 kPa).
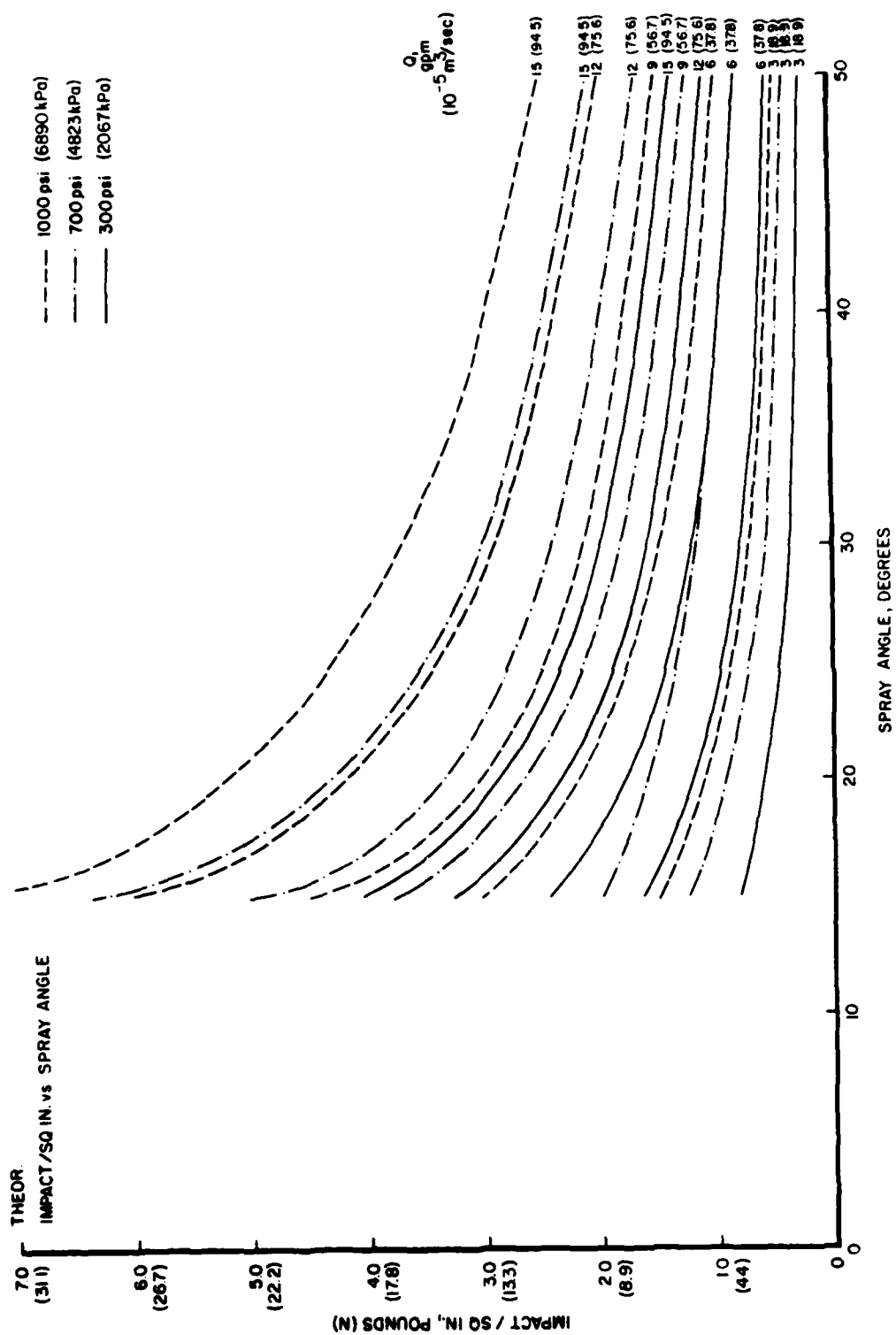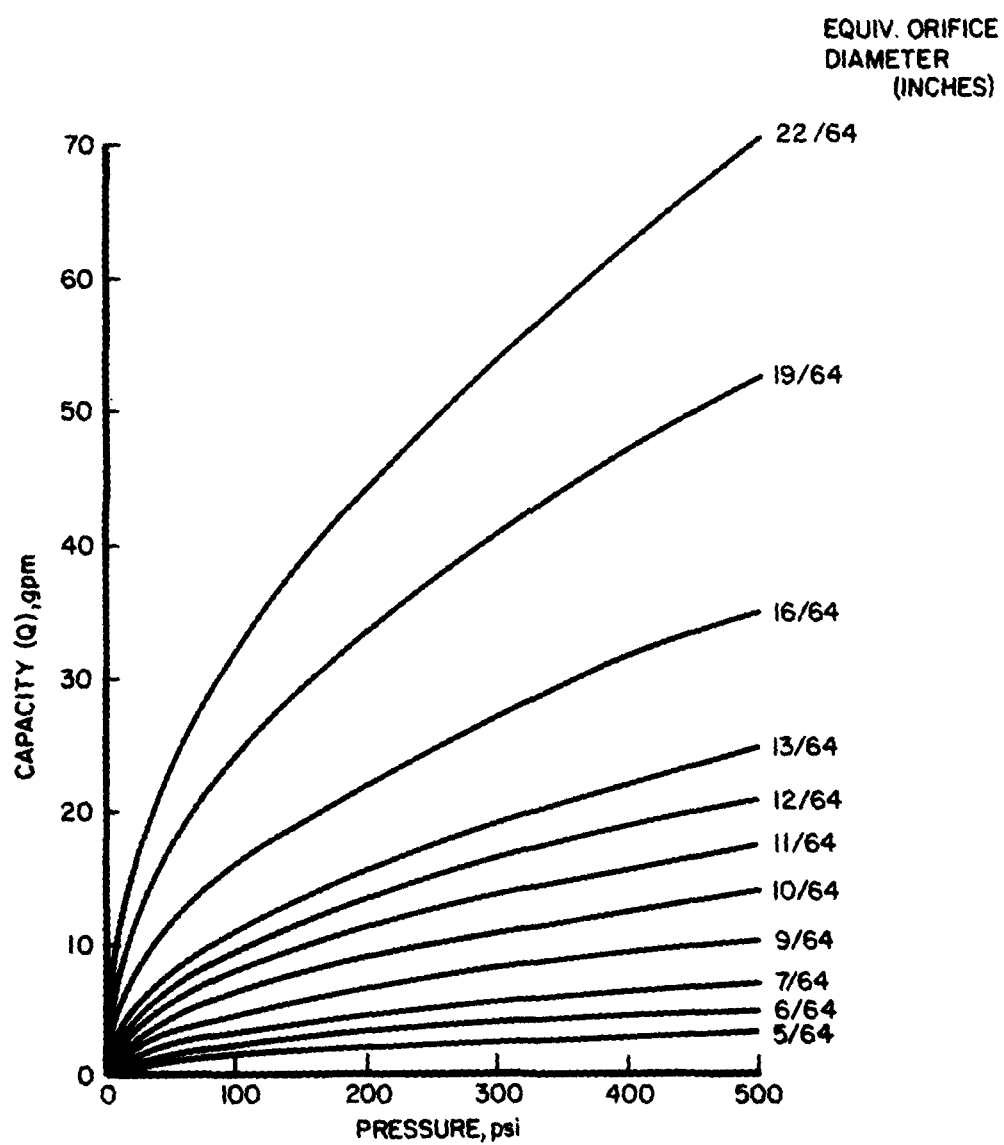
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EQUIVALENT ORIFICE DIAMETER (INCHES)	PRESSURE, psi					
	40	100	200	300	400	500
5/64	1.0	1.6 .88 1.8	2.2	2.7	3.2	3.5
6/64	1.5	2.4	3.4	4.1	4.7 .90 5.25	5.3
7/64	2.0 .89 2.26	3.2	4.5	5.5	6.3	7.1
9/64	3.0	4.7	6.7	8.2	9.5	10.6
10/64	4.0	6.3	9.0 .87 10.3	11.0	12.6	14.2
11/64	5.0	7.9	11.2	13.7	15.8	17.7 .90 19.7
12/64	6.0	9.5	13.4	16.4 .90 18.2	19.0	21
13/64	7.0 .90 7.9	11.1	15.7	19.2	22	25
16/64	10.0	15.8	22	27	32	35
19/64	15.0	24	34	41	47	53 .90 58.8
22/64	20.0	32 .91 35.3	44	55	63	71 .90 78.9

EXAMPLE FOR SOME VALUES $= \dfrac{\text{ACTUAL RATIO}}{\text{PREDICTED}}$

Figure A10. Capacities in gallons per minute (metric conversion factors: 1 in. = 25.4 mm; 1 psi = 6.89 kPa).

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